CONCRETE

ITS NATURE AND USES

A BOOK FOR ARCHITECTS, BUILDERS, CONTRACTORS, AND CLERKS OF WORKS

BY

GEORGE L. SUTCLIFFE

ASSOCIATE OF THE ROYAL INSTITUTE OF BRITISH ARCHITECTS; MEMBER OF THE SANITARY INSTITUTE; EDITOR AND JOINT AUTHOR OF "MODERN HOUSE-CONSTRUCTION," ETC.

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PREFACE TO SECOND EDITION.

SINCE the publication of the first edition of this work, which is now exhausted, great progress has been made in the art of "reinforcing" Concrete with rods, bars, or meshwork of iron or steel. A new Chapter on this important subject has therefore been included in the Second Edition, together with Additional Illustrations and Tables. The whole of the original text has also been revised, and somewhat extended.

The Author's thanks are gratefully tendered to those firms which have kindly placed information on reinforced concrete at his disposal, and also to the authors from whose works he has quoted.

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PREFACE TO FIRST EDITION.

Books on Limes, Cements, and Concretes have been almost invariably written by Civil Engineers for Civil Engineers. It seemed to the Author that a work, treating of the subject of Concrete from an Architect's point of view, might prove useful, not to Architects only, but to other persons engaged in Building. This idea was developed into a series of articles which appeared in *The Builder* from July to December, 1892, and the present work is a revised and extended edition of those articles.

Chapters XIV., XVII., and XXI. are entirely new; and the greater parts of Chapters XIII. and XXII., besides considerable parts of Chapters XVIII., XIX., XX., XXIV., and XXV., have also been added. The remainder of the work has been re-modelled to some extent, and further information has been inserted throughout; the number of illustrations has been more than trebled; and several new Tables have been included, some of which are here printed for the first time.

The Author gratefully acknowledges his indebtedness to the researches and works of many Engineers (notably those

of Mr. John Grant, Mr. Henry Faija, and Mr. Charles Colson), and to the current Architectural, Building, and Engineering journals, as well as to papers read before various professional societies, including the Royal Institute of British Architects. Particular mention should be made of the Institution of Civil Engineers, to which body he is indebted for much valuable information obtained from their Minutes of Proceedings. The courtesy of Mr. Thaddeus Hyatt, in allowing extracts to be made from his book entitled "Portland-Cement-Concrete combined with Iron" (which was printed for private circulation only), is also gladly mentioned. These various sources of information are duly stated in the body of the work.

September, 1893.

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CONCRETE.

CHAPTER I.

DEFINITIVE AND HISTORICAL.

Definition—Concrete and Béton—Historical: *Roman*, *Mediæval*, *Renaissance*, *Modern*—Uses.

DEFINITION.—Concrete is a solid mass formed from lime or cement, water, sand, and small irregular pieces of stone, brick, &c., by their "growing together" (as the word expresses it) when brought into contact with each other. The active agents in this solidifying process are the lime or cement and the water; the remaining ingredients are inactive, being merely bound together by the foregoing.

Different names have been given to the two classes of ingredients. The active ingredients are called the *matrix*, as they may be said to form a "womb," in which the inactive, known as the *aggregate*, are imbedded. Neither of these names we may say, is strictly accurate, but as they are the ones now usually adopted, we shall make use of them. Very often, however, the mortar,—that is, the mixture of lime or cement, water, and sand,—is spoken of as the *matrix*, and the remaining ingredients only are called the *aggregate*; this nomenclature has probably arisen from the fact that the strength of concrete, made with the same coarse ingredients, varies very nearly according to the strength of the mortar in which the coarser ingredients are imbedded, and not so much according to the strength of the lime or cement itself.

"CONCRETE" AND "BÉTON."—A distinction is sometimes made between the English word "concrete" and the French word "*béton.*" In France it is customary to mix the lime or cement with the sand and water, and thus to form mortar; the broken stones or other materials are then added to the mortar, and thoroughly mixed with it. In England, however, the general practice is to mix the whole of the ingredients dry, and, when the mixing is sufficiently advanced, to add water gradually, the ingredients being still further turned over during the operation.

Some writers limit the meaning of the word "concrete," by applying it only to concrete prepared in the English way; and the word *béton* is taken to mean concrete prepared in the French way. There does not seem much reason, however, in thus limiting the meaning of the word, for concrete is concrete, no matter how it is prepared, just as stone is stone whether it be formed by the aggregation of countless myriads of microscopic organisms, or merely by the consolidation of sand-grains. We shall use the word "concrete" in its wider sense, especially as this is the sense in which it is now generally used.

HISTORICAL: *Roman.*—The Romans were the first great concrete-builders, and some of their concrete structures have not been surpassed in magnitude to this day. They made use of it before the year 500 B.C. Vitruvius, who wrote in the first century after Christ, gives instructions for its manufacture. In his book on architecture, he describes how to make concrete pavements and floors, and concrete walls around wells. His specification for the concrete in the last instance might be substituted, without very much detriment, for the clauses in some modern specifications. He says (according to Gwilt's translation):—"In the first place, the purest and roughest sand that can be had is to be procured; then material is to be prepared of broken flint, whereof no single piece is to weigh more than 1 lb.; the lime must be very strong, and in making it into mortar, five parts of sand are to be added to two of lime; the flint work is combined with the mortar,

and of it the walls in the excavation are brought up from the bottom, and shaped* by wooden bars covered with iron." The Roman "libra," which we presume has been simply translated into "pound," was equal to nearly $\frac{3}{4}$ lb. avoirdupois of our weight, and therefore the pieces of flint were specified to be not larger than about 2 in. cubes; this size of aggregate would be used in similar walls to-day. Vitruvius also mentions the use of puozzolana, a volcanic earth or sand, which confers upon fat lime the property of setting under water.

Roman walls were almost invariably of concrete or rubble, faced with brick, stone, or marble. This facing was always thin. The bricks as a rule were triangular on plan, and measured about 11 in. along the face, and only 6 in. from the face to the apex of the triangle which extended into the wall. The stones were sometimes only about 2 in. square on the face, and less than 6 in. on the bed, and were laid with the diagonals of the square horizontal and vertical, forming what was known as *opus reticulatum.* In any case, the strength of the wall depended on the concrete or rubble, rather than on the facing. According to Professor Aitchison, the concrete of the Romans was not mixed together before deposition, but a layer of mortar was laid, and the aggregate then deposited upon it, and this in turn would be followed by another layer of mortar, and so on. Bond-courses of large flat tiles were introduced every 4 ft. or 5 ft.

But not only were walls and floors constructed in this manner; arches, also, and domes were built, sometimes with a mere skin underneath of thin tiles laid flat, having radial tiles bonding into the concrete at intervals, and sometimes with skeleton framework or ribs of bricks and tiles, the whole being covered or filled with concrete of considerable thickness.

The dome of the Pantheon, which was erected about the

* Professor Aitchison, A.R.A., renders the word "rammed" instead of "shaped," and this would bring the specification of Vitruvius still nearer to modern practice.

year 123 A.D., was until recently believed to be constructed of concrete with brick or tile ribs, but the researches of Mons. Chadanne in 1892 proved it to be of solid brickwork. In many buildings, however, the former material was freely used, and when we consider that the Romans had only fat lime and puozzolana to depend upon for the solidifying of their concrete, we are surprised at their boldness.

It is probable that the development of domed construction among the Romans was due in great measure to the material, concrete, of which many of their greatest works were built.

Their partiality for concrete was due to three or four causes. In the first place, the great bulk of the work did not require trained artificers, of whom there was often a scarcity, but could be done by slaves or labourers, of whom there were many; in the second place, the work could be executed much more rapidly than with bricks or dressed stone, and this, then as now, was an important consideration; again, in many places suitable building stone could not be obtained; and, finally (for the Romans doubtless studied economy,—they were such a practical people), concrete recommended itself for its cheapness.

Professor Middleton, in his recent work on "The Remains of Ancient Rome" (1892), gives his opinion that the brick facing of the Roman walls is not strong enough to support the concrete hearting while wet, and therefore that timber framing must have been used to support the walls during their construction. He thinks he has discovered proof of this in the Golden House of Nero, under the Thermæ of Titus, where upright grooves, 6 in. wide and 4 in. deep, for the reception of the timber posts, are visible in the walls, the grooves, however, being "afterwards filled up by the insertion of little rectangular bricks, so as to make a smooth, unbroken surface for the plastering."

It is of course possible that timber framing may have been used by the Romans, but we agree with Professor Aitchison, when he says that it seems odd, if timber framing were employed, "that so economical a people as the Romans

should have wasted time and money on this brick facing, which was to be covered with plaster or marble."* Apparently the rough brick or stone facing was adopted instead of a wooden framework. The bond-courses of flat tiles, extending through the whole thickness of the wall, seem to have been inserted partly to strengthen the facing, and point to the conclusion, that for such walls no timber frames were used. The Romans, however, appear to have discovered that it was possible, by using a timber framework, to do without the facing of stone or brick, and such walls were accordingly built.† Into the other details of concrete construction given by Professor Middleton, we cannot enter here. Suffice it to say that the strength of the concrete seems not to have lessened at all during the centuries of its existence, but rather to be greater to-day than ever.

In England examples of Roman concrete or rubble can be seen at Pevensey and Richmond, and other places.

Mediæval.—In the middle ages, concrete was frequently used not only in foundations but also in walls. We are told that the walls of the Castle of Badajos in Spain still bear the marks of the boarded frames, in which the concrete was deposited. In our own country, the Roman practice of employing facings of stone seems to have been universally adopted, and the concrete may perhaps be more correctly termed "rubble."

Although many examples of Norman concrete remain in excellent preservation, it must be confessed that in many other instances it has failed; vast piers, apparently of solid hewn stone, have yielded under the weight of superincumbent vaults and towers, and have proved to be mere shells of masonry filled with masses of more or less incoherent rubble.

Concrete was successfully employed in the Norman and Early English foundations of Ely Cathedral, in Salisbury

* *The Builder*, July 9, 1892.

† Mr. John Slater, B.A., in Carpenters' Hall Lecture on "Concrete," March 17, 1886.

Cathedral, Westminster Abbey, and in many of our castles. At Guildford Castle, which was erected in the latter half of the twelfth century, are concrete walls from 11 ft. to 14 ft. in thickness at the base; the aggregate consists largely of flints, and the walls were carefully faced with the same material. At Middleham Castle in Yorkshire the walls were faced with dressed stone; this has been removed in many places by successive generations of predatory builders, and the sound rubble hearting has been exposed to view. Masses of rubble lie amid the ruins, while one large unshapely mass remains poised on a comparatively slender pier of the same material.

We have said enough to show that good concrete will last for many centuries, but it must also be stated that much of the concrete we have mentioned has been protected, during a great part of its existence, by a facing of some other material.

Renaissance.—In the fifteenth and sixteenth centuries we find Alberti and Palladio describing the method of constructing concrete walls, and from them we learn that the system in use in those days was the same as the one used to-day, with, of course, slight modifications; then as now, boards were placed on each side of the intended wall, at the proper distance, and the space between was filled with mortar, pebbles, broken stone, &c.

Modern.—In more recent days, it was used by Sir Robert Smirke in the foundations of Millbank Penitentiary in 1811. Smirke's specification says that the concrete shall "consist of fine gravel or ballast, freed from slime, mud, and sand, except that a small portion of the latter shall be intermixed with the other material, in the proportion the architect shall direct, the whole to be well puddled and cast and mixed in lime-water." Smirke's specification is somewhat vague, but he knew how to deal with the gravel.

From this time forward, greater attention has been paid to the importance of concrete as a building material, until at the present day there is scarcely an architect who has not made use of it in some way or other. In 1835–6,

Mr. George Godwin, afterwards Editor of *The Builder*, read a paper entitled "The Nature and Properties of Concrete, and its application to construction up to the present period," before the *Royal Institute of British Architects*. In it he traces the use of concrete through various periods of architecture, and describes its use in his own day.

Apparently the first attempt in this century to use concrete on a large scale was made about 1835 by Ranger, who built a graving dock and sea-wall at Woolwich; the concrete consisted of grey-stone or hydraulic lime, and gravel, mixed with hot water. Mr. Bernays said in 1880 that the sea-wall was "a few years ago in remarkably good condition." Cottages of Roman cement concrete were built at Harwich in 1841, and Bridgewater in 1846, of Medina cement concrete near Osborne (Isle of Wight) in 1852, and of Portland cement concrete in the Isle of Thanet in the same year. The last were, according to Mr. Drake, perfectly sound and free from damp in 1872. In 1865 Mr. Tall patented a concrete-building apparatus or framework. In 1868 Mr. Drake patented his iron apparatus, and in the following six years "thousands" of buildings (says Mr. Drake), including mansions, houses, churches, chapels, warehouses, mills, &c., were built by means of it. Besides these, many other patents have been taken out for such appliances, among which we may name those of Osborne, Lish, Potter, Henley, and Broughton. We fear that many of them have been more ingenious than useful, and have proved of little benefit to their inventors.

The introduction of Portland cement, which is undoubtedly the strongest cement the world has ever known, contributed largely to spread the use of concrete in building, and although it has not effected that revolution in architecture, of which its enthusiastic admirers dreamed, yet it has proved itself to be an almost indispensable building-material, and has, on account of its great strength, and (in comparison with hydraulic limes and natural cements) its reliability, led to the employment of concrete for many purposes, for which lime-concrete was utterly unsuitable.

The experiments of Grant, Colson, Hyatt, and others have furnished valuable information which enables us to use the material in a more scientific and economical manner.

Uses.—Every architect uses it sooner or later in foundations. It is used in walls, floors, roofs, stairs, paving, drain-pipes, conduits, bridges, arches, lintels, building-blocks, and in all sorts of so-called "artificial stones." It is used alone or in combination with wood, iron, steel, fire-clay lintels, &c. There are even concrete doors and concrete telegraph-poles, and mill-chimneys have been built of it. Engineers have used it in the sea in vast monolithic masses, deposited *in sitû*, or in huge blocks weighing 200 or 300 tons each, or deposited in sacks, each weighing when filled as much as 100 tons; they have built of concrete, piers, breakwaters, docks, lighthouses, and have filled with it the caissons forming the foundations of the biggest bridges. Patents innumerable have been taken out for improvements in the methods of making and using concrete, and much money has been lost by unsuccessful inventors, but we advance by failures, and to-day concrete is used for a greater variety of purposes than ever before.

CHAPTER II.

MATRICES.

Classification—I. LIMES :—1. Rich lime—2. Poor lime—3. Hydraulic limes (Tables I., II., and III.)—4. Selenitic limes or cements.

CLASSIFICATION.—The ingredients of concrete are divided into two classes:—the cementing materials and the cemented, known respectively as *matrix* and *aggregate*. The former includes the various kinds of limes and cements, and also those earths or sands which, when mixed with ordinary lime, enter into chemical union with it, and cause it to "set" after the manner of hydraulic lime; the water used in mixing the concrete also falls into this class, for without it there would be no setting or hardening of any of the foregoing substances. The term "*aggregate*" includes the remaining materials used in concrete, such as sand, gravel, broken stone and brick, burnt clay and shale, &c.

The various matrices used in concrete * may be classified thus† :—

I. LIMES.—1. *Rich, or pure, or fat lime.*
2. *Poor, or impure, or meagre lime.*
3. *Hydraulic limes.*
4. *Selenitic limes, or cements.*

II. NATURAL CEMENTS.—1. *Roman cement, &c.*
2. *Plaster of Paris, &c.*

* *Asphalt* and *Tar-Concrete* may undoubtedly be considered of the nature of concrete, but they are beyond the scope of this work.

† *Puozzolanas*, &c., will be mentioned in the Chapter on Sand.

III. ARTIFICIAL CEMENTS.—1. *Parian cement, &c.*
2. *Slag cement.*
3. *Portland cement.*

IV. WATER.—1. *Fresh water.*
2. *Sea water.*

I.—LIMES.

Limes are not all suitable for use in concrete. Some of them possess the property of setting under water to a considerable extent, and will eventually attain great strength in such a position, while others are almost entirely soluble in water, and are therefore useless in damp situations. Some have an inherent power of hardening when mixed with water and exposed to the air, whereas others merely dry to a friable mass.

1. RICH LIME.

COMPOSITION.—Rich lime is burnt from stones which consist almost entirely of carbonate of lime (*calcium carbonate*), such as chalk, marble, and some of the varieties of building stone. Other substances—silica, alumina, magnesia, oxide of iron, &c.—may be present to the extent of about 10 per cent. The silica is present in the form of sand, and therefore has no beneficial effect on the setting of the lime.

CALCINATION.—We do not propose to enter into a detailed description of the modes of manufacturing either limes or cements; it will be sufficient for our purpose if we state broadly the effects of the processes of manufacture. By the burning of calcium carbonate, the water and carbonic acid gas which it contains are expelled, and *calcium oxide*, commonly called "quicklime," remains. The chemical equation, omitting the water, is thus expressed :—

$$\underset{\text{Calcium carbonate.}}{COCaO_2} = \underset{\text{Calcium oxide.}}{CaO} + \underset{\text{Carbonic acid gas.}}{CO_2}.$$

Slaking.—When rich lime arrives on the building-site for use in mortar or plaster, it is in the form of quicklime (calcium oxide), but in that state it is not ready for use. It must first be slaked by the addition of water. Quicklime readily combines with water, and is, if exposed to the atmosphere, gradually slaked by absorbing moisture therefrom; in this slow way quicklime is slaked for agricultural purposes, the little white heaps in fields being a familiar sight in some parts of the country. If, however, a considerable quantity of water be added, the calcium oxide combines with it with much violence and heat, falling to a powder two or three times the bulk of the lime prior to slaking. This increase in bulk, when quicklime comes into contact with water, must be borne in mind, for the fact has an important bearing on the subject of the proper use of hydraulic limes and cements. The chemical change caused by slaking is thus expressed:—

$$\underset{\text{Calcium oxide.}}{CaO} + \underset{\text{Water.}}{H_2O} = \underset{\text{Calcium hydrate.}}{Ca(HO)_2}.$$

Setting.—*Calcium hydrate*, or as it is usually termed, slaked lime, is soluble in water; consequently a paste made from it does not set or harden under water. There is nothing in its composition, as there is in hydraulic limes and cements, to give it the power of setting merely on the addition of water. Calcium hydrate, if placed in foundations, or in the interior of thick walls, where little or no air can obtain access to it, will remain calcium hydrate for years without any increase of strength whatever. In air, however, a certain amount of chemical action takes place, which results in the hardening of the lime. This is effected by the absorption of CO_2 from the atmosphere, but the setting is more apparent than real, for it is only skin deep. And not only is this re-formation of carbonate of lime ($COCaO_2$) a mere skin, it is also of no great strength. It is probable, also, that the lime dissolved by the water used in slaking the lime and making it into mortar, and also by the slow absorption of moisture from the air, gradually

crystallises, and therefore assists the hardening of the mortar, but as about 700 parts of cold water are required to dissolve one part of lime, the crystallisation is decidedly slow. Mortar from the interior of the Pyramids, where it has not been exposed to the action of the air, still contains free lime, although it is 5,000 years old.

Another difficulty attending the use of rich lime is its great shrinkage or contraction during the process of hardening; in order to obviate the ill effects of this, a large quantity of sand is mixed with it to form mortar. The sand also fulfils another office, for it renders the mortar more porous, and therefore assists the passage of air and moisture to every part of it.

No more need be said to show the unsuitability of rich lime, not for concrete only, but for all manner of building work where cohesive and adhesive strength is required, but a knowledge of the changes which take place in the calcining, slaking, and setting of rich lime is necessary for the proper apprehension of some of the changes which take place in hydraulic limes and cements, and also of the difficulties and dangers attending their use.

Uses.—Rich lime is used for agricultural purposes, for internal plastering, and in the manufacture of Portland cement, slag cement, &c.

2. Poor Lime.

Poor lime is burnt from limestones, which contain a considerable quantity (say, from 10 to 30 or 40 per cent.) of matter, nearly the whole of which is in such a state as to have no power of combining with the lime and exerting a beneficial effect on the setting of it. In other words, poor lime is rich lime very much adulterated. It has all the disadvantages of rich lime, and one or two more. It slakes more sluggishly than rich lime, does not increase as much in bulk or fall to as fine a powder, and requires more careful screening and grinding on being made into mortar. It ought never to be used for concrete.

3. Hydraulic Limes.

Definition.—These limes have been so called from the property they possess of setting under water. The word "hydraulic" used in this sense is somewhat of a misnomer, seeing that it is derived from the Greek *hydor*, water, and *aulos*, a pipe, and really refers to the conveyance or use of water by means of pipes. Custom, however, has sanctioned its use in the sense of "setting under water," and also the use of the noun derived from it—"hydraulicity," which is taken to signify "the property or power of setting under water."

Subdivisions.—Hydraulic limes vary exceedingly in their composition, and consequently in their hydraulicity. The quantity of *lime* present in some is only about 60 per cent., while in others it is 80 or even 90 per cent.; and the time required for the lime to harden under water varies from one or two days to three or four weeks. This variety has given rise to a subdivision of the class into (1) *feebly*, (2) *moderately*, and (3) *eminently* hydraulic, but these subdivisions are somewhat indefinite, merging into one another, and ranging from the verge of rich and poor limes on the one hand, to the verge of natural cements on the other. Moreover, no lengthy list of British hydraulic limes has ever been made in which the various limes have been classified under these three heads. The nomenclature, however, affords a convenient method of expression, although it has not much practical or scientific value.

Composition.—The most important hydraulic limes owe their hydraulicity to the clay, which forms part of the raw stone. In stones producing feebly hydraulic limes, the clay may be about 8 or 10 per cent. of the whole; moderately hydraulic limes, from 10 to 15 per cent.; and eminently hydraulic limes, from 15 to 20 or even 30 per cent. Any excess of clay over 30 per cent. is detrimental to the setting power and strength of the lime.

Another class of limes consists of those which contain little or no clay, but are rendered hydraulic by the magnesia

present in them. In the raw stone, producing moderately hydraulic lime, the carbonate of magnesia may be 30 or 40 per cent. of the whole, and the carbonate of lime 50 or 60 per cent. Nearly all limes and cements contain a small quantity, say, 1 or 2 per cent. of magnesia, but it is only when the magnesia reaches about 30 per cent. of the whole stone, that it confers a moderate hydraulicity. The most important class of hydraulic limes, however, is the one in which clay plays a prominent part, and as clay is the ingredient which confers hydraulicity on that most important of all limes and cements, namely, Portland cement, more attention has been devoted to the study of its action in combination with lime, than to that of magnesia with lime.

Undoubtedly the most important class of hydraulic limes consists of those which are burnt from the Blue Lias limestone. They vary considerably in their setting power and ultimate strength. The Blue Lias stone is found at Lyme Regis in Dorsetshire; at Pylle and Watchet in Somersetshire; at Barrow-on-Soar in Leicestershire; at Rugby, Stockton, Wilmcote, and other places in Warwickshire; at Barnstone, near Nottingham; at Kirton Lindsay in Lincolnshire; at Aberthaw in Monmouthshire; at Whitby in Yorkshire, and at various other places in England. At many of these places the stone is used for the manufacture of Portland cement, which is quite equal to that made from chalk and clay or mud, as at Rochester and other places on the Medway and the Thames. The lias limes obtained at Aberthaw, and in Leicestershire and Warwickshire, have, perhaps, the best reputations, but, for reasons already stated, no actual comparison can here be instituted.

Feebly hydraulic limes are obtained in many parts of the country, but have merely a local reputation. Some of those used in London are obtained from Sussex.

Other hydraulic limes are burnt from the carboniferous limestones, as at Holywell in Flintshire, and others again from the magnesian limestones in Yorkshire, Derbyshire, and other counties. Limes of the latter kind, owe their

hydraulicity chiefly to the chemical union of the lime and magnesia on the addition of water. They frequently attain considerable strength, but the author is not aware of any actual tests having been carried out to show the difference between them and other hydraulic limes. An analysis of a good hydraulic lime, obtained from a magnesian limestone near Doncaster in Yorkshire, is given in the table of analyses, page 89.

Calcination.—When limestone containing clay is burnt, the moisture and carbonic acid gas are expelled at a comparatively low temperature, and the clay is split up into its component parts, silica and alumina; the silica is present in the form of *hydrated silicic acid* ($SiHo_4$), and combines, as far as possible, with the lime to form *calcium silicate.* Silica frequently occurs in limestones in the form of sand (quartz and flint, SiO_2), but is then quite insoluble and consequently useless. Analyses ought, therefore, to say in what form the silica occurs; a "poor lime" may contain a proper proportion of silica, and yet possess no hydraulicity whatsoever.

Analyses.—There is, of course, a great difference in the composition of hydraulic limes, and it is scarcely possible to classify them according to their hydraulicity. A few analyses are given in Table XII. (page 89), in order that the composition of some well-known limes may be seen at a glance, and compared with one another, and with other limes which may at any time be submitted for consideration.

Weight.—The weight of hydraulic limes varies considerably, some when ground being only a little heavier than powdered white chalk lime, and others being only a little lighter than Portland cement. The extreme limits may be considered to be 60 lbs. and 100 lbs. per "striked" bushel (about 1·28 cub. ft.), but the weight varies not only according to the composition and degree of calcination of the lime, but also according to the fineness, freshness, mode of filling the measure, &c. Lumps of Halkin Mountain lime weigh about 140 lbs. per bushel; the slaked lime obtained from these, weighs only 64 lbs. per bushel. The

weight of hydraulic lime must not be taken as the measure of its hydraulicity.

Slaking.—In all hydraulic limes there is an amount of quicklime (CaO) which has escaped combination with silica and alumina; this amount is very large in the most feebly hydraulic, very small in the most eminently hydraulic. When water is added to the lime, the oxide of lime present in it is converted into hydrate, as in the case of rich lime, but the action is less violent and slower in proportion to the quantity of silica and other ingredients which the lime contains. Instead of falling to a powder in a few minutes, lumps of hydraulic lime may not slake in less than one or two days, and some of the best may take a week; there is little or no vapour evolved, and the increase of bulk is, in the best kinds, comparatively small. But in all hydraulic limes there is a certain amount of slaking action, and this involves a corresponding increase of bulk. When a limestone produces by calcination a substance which, while possessing hydraulic properties, exhibits no slaking action at all, that substance is known as a cement.

The slaking should be thoroughly effected before the lime is made into mortar, otherwise there will be a danger of the cohesion of the latter being destroyed or impaired by the increase in bulk consequent on the gradual hydration of the quicklime in it after the setting has commenced. We have already said that an excess of clay is detrimental; such a lime, when completely calcined, may set rapidly, but when placed in water will soon exhibit cracks, steadily increasing, or will gradually soften throughout. Sometimes hydraulic lime is kept in a shed for a week or more after being slaked, and the hard lumps which have resisted the action of the water are removed before the lime is mixed with sand in the mortar mill; such storing is not beneficial.

There are two or three ways of slaking hydraulic lime-lumps, but the most common method is the one known as "drowning." A basin of sand, which may with advantage be coated with lime-paste to render it more impervious, is formed, and the lumps of lime are spread in it to the depth

of 6 in. or 8 in. A quantity of water, varying in inverse proportion to the hydraulicity of the lime, is then added. The Halkin Mountain lime requires about 45 gallons of water per ton, and becomes, when slaked, three times the bulk of the lump lime. The Barnstone Blue Lias lime requires about 40 gallons of water to the ton. Excess of water reduces the lime to a paste instead of a powder, and is injurious.

Gillmore says that fresh water should be used for slaking lime, as sea-water in all cases causes less increase of bulk.

After the water has been added, the heap is covered with sand or ashes, or with a tarpaulin, in order that the heat may be retained in the mass. This last precaution is important, because hot water is more active than cold in slaking lime, and steam is still more active; the vapour evolved during slaking greatly assists in disintegrating the harder lumps. The heap should not be disturbed for one or more days,—not, in fact, until the lumps have been as far as possible reduced to a fine powder. This is the object of slaking, for coarse particles, which are frequently the hard, well-burnt part of the lime, may gradually slake after being made into mortar, and so injure the mortar; while, on the other hand, they may prove, if reduced to powder, the very best part of the lime.

Grinding.—The more hydraulic the lime is, however, the more difficult it becomes to pulverise it by slaking; mechanical means must, therefore, be resorted to. The pulverisation may be effected by the manufacturer, in which case the lumps are ground dry, and the lime is sold as "ground lime;" or it may be effected on the building-site by grinding the lime in a mortar-mill. This may be done for three or four minutes dry, then the sand may be added, and in about two or three minutes more the necessary amount of water may be poured into the pan, and the grinding continued for about a quarter of an hour. In windy places dry grinding is a wasteful operation. It is advisable to mix even lime ground by the manufacturer in a mortar-mill, as the manufacturers frequently do not grind the lime

sufficiently fine. When a mortar-mill is not available, the lumps should be screened from the slaked lime, and thrown away.

Many hydraulic limes can only be obtained in lumps as drawn from the kilns; others, however, can be had either in lumps or ground. The lump lime (or "shell" lime, as it is sometimes called) is used chiefly for mortar, as this is, as a rule, ground in a mortar-mill, but the ground lime is preferable for concrete, as a mortar-mill is not usually employed in preparing this material, and some of the lumps of lime are hard enough to resist for a long time, or even altogether, the influence of water, but when finely ground become an energetic part of the lime.

It is very seldom, indeed, that any particular degree of fineness is specified by architects or guaranteed by manufacturers. The Aberthaw lime is usually ground so that not more than 15 per cent. remains on a No. 30 sieve, (that is, a sieve with 900 meshes to the square inch,) but can be more finely ground when required. When we compare this with the fineness of Portland cement, which often leaves less than 10 per cent. on a sieve with 2,500 meshes to the square inch, we cannot fail to notice the great difference between the two: but, of course, there is a great difference in the cost as well. Fineness of grinding is important, for, other things being equal, the more finely ground the lime is, the more sand will it bind together; but half a loaf is better than no bread, and any grinding better than none.

Setting.—The chemistry of setting will be considered hereafter. It will be sufficient to state now that setting and hardening are due mainly to crystallisation, brought about by the action of water on the silicate and aluminate of lime and not as in the case of fat limes, by mere absorption of carbonic acid gas from the atmosphere.

Testing.—The test for tensile strength, which is so important a test of neat Portland cement, cannot fairly be applied to neat hydraulic lime, as its cohesive strength is very small. When lime is tested, therefore, the briquettes contain usually three or more parts of sand. The adhesive

strength of hydraulic lime is sometimes tested by uniting two bricks or stones with mortar and ascertaining the force required to pull them apart at a certain age. The resistance of various hydraulic limes to crushing has been occasionally ascertained.

A great many experiments have been made by different persons on the strength of Portland cement, but not many have been made with the various hydraulic limes. One reason, doubtless, is the great difference which exists between different limes, and the consequent impossibility of formulating a series of standard tests which shall be applicable in all instances. Hydraulic limes are therefore usually selected empirically, and not from knowledge based on any scientific tests. They take, as a rule, much longer time to harden, and attain less ultimate strength, than Portland cement; the testing of them is therefore more tedious, and, adds Mr. Grant, years would be required to get sufficient tests to form an accurate opinion of their merits.

Tensile Strength.—In an appendix to a paper read by Mr. Grant before the *Institution of Civil Engineers*, in 1880, he gave the results of experiments made to ascertain the tensile and compressive strengths of various limes and cements, mixed with different proportions of sand. The tests for tensile strength were made on briquettes having an area at the neck of $2\frac{1}{4}$ square inches ($1\frac{1}{2}$ in. by $1\frac{1}{2}$ in.); the sand used in gauging the briquettes weighed 96 lbs. per bushel. Five briquettes were kept in air and five in water, and all were tested twelve months after gauging. Table I., showing the tensile strength in lbs. per square inch, has been prepared from that of Mr. Grant.*

One point will be at once noticed on examining the table, and that is the greatly increased strength attained by the *lime* briquettes when kept in water. In the case of No. 1 (Grey lime), the briquettes kept in water were 36 per cent. stronger than those kept in air; while in the case of No. 5

* *Proceedings of the Institution of Civil Engineers*, vol. lxii. (1879–80), part iv.

TABLE I.—TENSILE STRENGTH (in lbs. per sq. in.) OF LIMES AND CEMENTS.

No.	Limes and Cements.	Weight per bushel.	How kept.	Neat.	1—1	1—2	1—3	1—4	1—5	1—6	1—8	1-10	1-12	Average Ratios of strength. Wet.	Average Ratios of strength. Dry.	Ratios of strength between wet and dry briquettes.
		lbs.		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.			
1	Grey lime	—	Wet	—	—	—	68	57	45	28	—	—	—	30	—	136
		—	Dry	—	—	—	50	44	30	21	—	—	—	—	23	100
2	" " Selenitic	—	Wet	—	—	—	141	140	87	65	—	—	—	66	—	150
		—	Dry	—	—	—	128	65	55	40	—	—	—	—	40	100
3	Lias lime	—	Wet	—	—	—	96	60	47	27	—	—	—	35	—	151
		—	Dry	—	—	—	48	49	32	23	—	—	—	—	25	100
4	" " Selenitic	—	Wet	—	—	—	132	99	72	80	—	—	—	59	—	161
		—	Dry	—	—	—	79	63	44	52	—	—	—	—	38	100
5	Lias lime	—	Wet	—	—	—	81	61	44	34	—	—	—	34	—	205
		—	Dry	—	—	—	40	28	21	18	—	—	—	—	17	100
6	Selenitic lime ...	—	Wet	—	—	—	148	129	84	74	—	—	—	66	—	130
		—	Dry	—	—	—	124	80	72	58	—	—	—	—	54	100
7	" Rugby Lias ...	—	Wet	—	—	—	151	102	77	66	—	—	—	61	—	186
		—	Dry	—	—	—	92	59	33	29	—	—	—	—	34	100
8	" Aberthaw lime	—	Wet	—	—	—	204	147	123	76	—	—	—	84	—	167
		—	Dry	—	—	—	128	84	72	—	—	—	—	—	(54)	100
9	Rugby Lias cement	74	Wet	—	—	—	142	110	75	46	—	—	—	57	—	185
			Dry	—	—	—	78	63	40	20	—	—	—	—	32	100
10	Portland cement .	114	Wet	467	334	259	216	171	143	124	102	61	57	100*	—	105·6*
			Dry	471	339	238	198	164	144	113	53	45	32	—	100*	100 *
11	" "	120	Wet	649	406	245	195	140	124	100	63	56	43	85*	—	100 *
			Dry	552	357	213	180	161	131	99	70	52	41	—	92*	97·9*

* Of mortars containing 3, 4, 5, and 6 parts of sand.

(Lias lime) the increase of strength was no less than 105 per cent. The difference is not so marked with Portland cement; indeed, if we consider only the four mortars containing 3, 4, 5 and 6 parts of sand, the Portland cement, No. 10, was only 5·6 per cent. stronger when kept in water, while No. 11 was actually 2·1 per cent. weaker than when kept in air. If, however, we consider the whole of the Portland cement tests, we find that No. 10 gained on the average 7·6 per cent., and No. 11, 8·9 per cent., by being kept in water.

This fact of the increase of strength due to the mortar being kept wet, should be borne in mind, as it is often turned to practical account in the laying of concrete floors and in other work. At the same time, however, it must be remembered that increase of strength occurs only in those cases where the mortar or concrete is covered with water *after* it has been deposited and has begun to set. Concrete actually deposited in water is invariably weaker than similar concrete deposited in the air; this is due to the washing away by the water of the finest particles of the lime or cement, and to the formation of a milky substance—which the French call "*laitance*"—which has no setting properties.

The proportions of the lime or cement and the sand, in this series of experiments, were measured by volume and not by weight. This is the mode of measurement invariably adopted in making mortar and concrete, but it is one seldom used in testing Portland cement. The results given in the table are really misleading as to the relative values of the limes and cements, if the difference between their weights be not borne in mind; for, as limes and cements are sold by weight, their relative value can only be ascertained by taking the weight into consideration. For instance, compare the 1 to 3 mortars made with Rugby Lias cement (No. 9) and Portland cement (No. 11); the former, kept in water, had a strength of 142 lbs. per sq. in.; the latter, 195 lbs.; but the weight of cement in the former mortar was only as 74 is to 120 in comparison with that in the latter. To put it another way—a bushel of the Rugby

Lias cement, weighing 74 lbs., is mixed with 3 bushels of sand, weighing 288 lbs.; the weight of cement to sand is therefore approximately as 1 is to 4: in order to obtain this ratio in the case of the Portland cement in question, only about three-fifths of a bushel of cement would have to be mixed with the 3 bushels of sand, and this gives a mortar having the cement and sand in the proportion of 1 to 5. Curiously enough, the strengths of the Rugby Lias cement mortar, 1 to 3, and of the Portland cement mortar, 1 to 5, are almost identical, being 142 and 143 lbs. respectively. A true comparison of the relative strengths per unit of cost can, in this way, be instituted. The Rugby Lias cement in the remaining tests given in the table, does not compare as favourably with Portland as in the one just considered, and the enfeebling effect of additions of sand is not by any means as great with the latter as with the former cement.

Compressive Strength.—Table XXI., p. 183, shows the compressive strength of concrete made with the limes and cements mentioned in Table I., and exhibits the immense superiority of Portland cement under a crushing strain.

Adhesive Strength.—The following table has been compiled from the circular issued by the Selenitic Cement Company. It shows the force per square inch of mortar-joint required to tear apart bricks after they had been united for twenty-eight days by mortars of various kinds:—

Table II.—Adhesive Strength of Limes and Cements, in lbs. per sq. inch.

Kind of Lime or Cement.	Proportions of Lime or Cement, and Sand.			
	1 to 3.	1 to 4.	1 to 5.	1 to 6.
	lbs.	lbs.	lbs.	lbs.
White Chalk Lime	$4\frac{3}{4}$	—	—	—
" " Selenitic	$10\frac{1}{2}$	$9\frac{3}{4}$	$12\frac{1}{4}$	$10\frac{3}{4}$
Barrow Lias Lime	9	$6\frac{3}{4}$	—	—
" " Selenitic	27	21	20	20
Portland Cement	—	23	$16\frac{1}{4}$	$15\frac{1}{2}$

Halkin Mountain lime made into mortar with one part of sand and one of ashes, has been found to have an adhesive strength of 28·7 to 34 lbs. per sq. in. at 168 days, tested with bricks as above.

COMPARISON OF GREY LIME AND PORTLAND CEMENT.—Careful experiments have been made by Mr. Charles Colson* to ascertain the relative values of mortars containing grey lime, Portland cement, and mixed lime and cement, the briquettes being kept in air. The results are summarised in Table III., and a column is added showing the relative cost per unit of strength.

TABLE III.—TENSILE STRENGTH OF GREY LIME AND PORTLAND CEMENT MORTARS, &c., AT THE AGE OF SIX MONTHS.

No.	Composition by Volume. Portland Cement.	Grey Lime.	Loam.	Sand.	Water.	No. of Tests.	Average strength in lbs. per sq. inch.		Ratios of strength.	Cost per cub. yd. of mortar.	Relative Cost per unit of strength.
										s.	
1	—	1	—	2	1·33	17	27·13	36·88	1	11·83	100
2	—	1	—	2	1·33	27	47·09				
3	—	1	—	2	1·33	27	36·44				
4	1	—	—	6	1·25	15	103·79		2·81	11·56	35
5	1	—	—	8	1·66	20	68·8		1·86	9·93	45
6	1	--	—	10	2	35	50·16		1·36	8·88	55
7	1	·5	--	6	1·5	70	73·47		2	12·2	52
8	1	·66	—	8	2	74	58·94		1·6	10·72	57
9	1	·83	—	10	2·5	85	42·34		1·14	9·75	72
10	1	—	·5	6	1	21	60·8		1·64	11·44	59
11	1	—	·66	8	1·33	25	38·43		1·04	9·82	80
12	1	—	·83	10	2	19	28·66		0·77	8·76	96

In the foregoing tests, three samples of grey lime were used, and were found to vary greatly in strength. The fractured briquettes of the lime-mortar "showed that induration . . . had penetrated only to the extent of from

* *Proc. Inst. C. E.* vol. liv. (1877-8, part iv.).

one-eighth to three-sixteenths of an inch, but in the majority of instances to only one-eighth of an inch. The remainder of the area, although dry and moderately hard, had become so mainly from the evaporation of the moisture originally contained in the mass, and in no sense from the absorption of carbonic acid. It was possible, moreover, to crush it in the hand without any great exertion of force."

The loam used in the tests was "yellow, fresh-dug, and rather damp." The quantity of water includes that required for slaking the lime.

The Portland cement mortars (Nos. 4, 5, and 6) were so raw and harsh "that it would be practically impossible to use them in a satisfactory manner." In order to render them "more plastic and tenacious," lime or loam was added in the remaining tests, to the extent of one-twelfth of the volume of the sand, this being the least quantity that would render the mortars convenient for working. Both these ingredients act injuriously on the mortars, and materially enhance the cost per unit of strength. Loam, however, is much the worse of the two. If we compare tests 5 and 11, we find that the addition of the small quantity of loam lessens the value of the mortar more than 50 per cent. The real economy, therefore, of using *clean* sand—artificially washed if necessary—is evident.

STORING.—All limes and cements have a tendency to absorb moisture, and if they are left too long in a damp atmosphere, they will be entirely spoilt. As we have already seen in the case of rich limes, moisture causes the hydration of the lime, converting the quicklime (*calcium oxide*) into *calcium hydrate*, the latter having two or three times the bulk of the former. The same action takes place in hydraulic limes, but not to so great an extent. For this reason, however, manufacturers frequently warn their customers that, if ground lime is not used at once, it should be emptied out of the bags, as otherwise the expansion of the lime will probably burst them. The lime can be stored either in casks or on a dry floor in a warehouse, and may then be kept for some weeks, or even months, without

detriment. This air-slaking causes the lime to set more slowly than when fresh, and this is frequently an advantage. For works in running water, where rapidity of set is necessary, ground lime is often used fresh.

USES.—Hydraulic lime cannot, of course, be used for as many purposes as Portland cement. No one would think of using it now for the surface of paving, for floors, sewers, moulded work, or artificial stone; but it is largely used for concrete in ordinary foundations and ground layers, and for mortar; it has also been employed successfully for concrete in the walls of buildings, but, in England at any rate, it is now superseded for that purpose by Portland cement.

Mixtures of lime and Portland cement have also been used for the matrix of concrete, the result being of course, a stronger concrete than if the matrix had been entirely of lime. But mixtures of this kind are of doubtful advantage, and whenever they are used great care must be exercised that the lime is thoroughly slaked before the cement is added to it, as otherwise the concrete may "blow."

4. SELENITIC LIMES OR CEMENTS.

HISTORY.—Selenitic lime or cement was first made and patented by General Scott about 1870, and a company was soon formed to carry on the manufacture of it. The patent expired some years ago, and selenitic lime is now made at many lime and cement works in various parts of the country, but especially from the Lias lime in Warwickshire and Leicestershire.

COMPOSITION.—The invention consisted in the addition of a certain quantity of sulphate of lime to the natural lime. Sulphate of lime ($CaSO_4$) occurs naturally in various forms, as *selenite*, *gypsum*, and *alabaster*. It is from the first of these that selenitic lime received its name. Plaster of Paris is calcined from the second, namely, gypsum, and Robinson's cement (to be mentioned hereafter) is calcined alabaster. Keene's, Martin's, and Parian cements also consist chiefly of

sulphate of lime. But the point, in which selenitic lime differs from all these, is that the sulphate is present only in a small quantity, and does not form the bulk of the lime or cement. In fact, about 5 per cent. of plaster of Paris added to lime, converts it into a selenitic lime. The better the natural lime is, the better, it is said, will be the selenitic lime manufactured from it; that made from grey lime will be inferior to that made from Blue Lias lime. This statement is not confirmed by Mr. Grant's experiments already quoted (Table I., p. 20).

TENSILE STRENGTH.—There can be no doubt that the process increases both the cohesive and adhesive strength of limes to a great extent, but Mr. Grant's tests do not show as great an increase of strength as do those published by the Selenitic Company. Perhaps this is not to be wondered at. The experiments go to prove that, at the end of twelve months, a mortar composed of one part of selenitic lime and five parts of sand is equal in tensile strength to a mortar composed of the same lime (but without plaster of Paris) and three parts of sand. Selenitic treatment improved the grey lime 100 per cent. when kept in air and 109 per cent. when kept in water, but improved the Lias lime (No. 2) only 57 per cent. in air and 66 per cent. in water; however, the strength of the latter lime, when made into mortar with six parts of sand, was about 25 per cent. more than a similar mortar made from the former.

ADHESIVE STRENGTH.—We have already said that selenitic treatment improves the adhesive strength of limes; Table II. shows this conclusively. The great sand-carrying capacity of selenitic lime is one of the chief advantages claimed for it, and, according to the table, it is in this respect superior to some kinds of Portland cement.

COMPRESSIVE STRENGTH.—The series of experiments, made by Mr. Grant and given in Table XXI. (p. 183), shows that concrete made of selenitic grey lime, gravel, and sand, is 71 per cent. stronger than a similar mixture of ordinary grey lime, gravel, and sand, and that the selenitic treatment increases the strength of Lias lime concrete about 38 per cent.

These figures are the average of thirty tests of 6-in. cubes in each case. But the strongest selenitic lime tested by Mr. Grant, namely, selenitic Rugby Lias, gave results far below those given by Portland cement, tested in the same manner. The resistance to crushing of 6-in. cubes of concrete, made from one part of selenitic Rugby Lias and six parts of gravel and sand, was 9·28 tons, while similar cubes of Portland cement concrete crushed at 25·19 tons.

STORING.—Like all other limes and cements it should be kept perfectly dry, if not used fresh.

USES.—Selenitic lime is used in mortar and concrete, but opinions differ as to the value of the treatment. Certainly engineers do not use it in important works, but prefer Portland cement. A series of experiments, made by Mr. E. C. Clarke in connection with the Boston (U.S.A.) Main Drainage Works (1878–84), convinced him that selenitic treatment "had not improved the cement sufficiently to compensate for the increased cost." The late Mr. G. E. Street, R.A., used selenitic lime in the concrete foundations, &c., of the Law Courts, after its value had been demonstrated by a series of experiments carried out by one of his clerks-of-works; and it was used in several other important buildings at the same time. It is more frequently adopted for plastering than for concrete, and has been used for that purpose in many large works, including the Law Courts and the Manchester Town Hall.

CHAPTER III.

MATRICES—(*continued*).

II. Natural Cements:—1. Roman, Medina, and kindred cements (Table IV.)—2. Plaster of Paris (Table V.), Robinson's cement (Table VI.).

II.—NATURAL CEMENTS.

1. Roman, Medina, and Kindred Cements.

History.—The discovery of natural cement in England is due to Parker, who in 1796 took out a patent for its manufacture. Up to that time, English architects and engineers had relied chiefly on puozzolana from Italy for rendering lime hydraulic, and it was probably for this reason that the name "Roman Cement" was given to the new discovery.

Raw Materials.—The cement was originally obtained by the calcination of nodules, or septaria, found in the London clay, and afterwards of those dredged from the Solent. These contain more clay than the raw stone either of hydraulic lime or Portland cement. The latter contains about 25 per cent. of clay, &c., while Roman cement contains from 25 to 35, or even 40 per cent.

Besides the cement more particularly known as "Roman," there are others which are very similar, but which have received different names; such as "Medina Cement," made in the Isle of Wight; "Atkinson's Cement," made at Whitby in Yorkshire; and "Harwich Cement" and "Sheppey Cement," named from the places of their manufacture. "Calderwood Cement," made near Glasgow, is of similar character.

Some of the Carboniferous limestones of Derbyshire, &c., and of the Lias limestones of Warwickshire, yield on cal-

cination cements approximating to the Roman cement. At Boulogne, in France, a natural cement is found, which, from its similarity, both in composition and action, to Portland cement, has been called "Natural Portland." America, however, is the great home of natural cements, and there such cements have received most attention.

In England the Roman and kindred cements have been largely superseded by Portland cement, because of the superior strength of the latter and its greater capacity for sand. There are, however, situations in which the natural cements can be used with advantage on account of their quickness of set, but there are Portland cements manufactured now which set almost as quickly as the natural cements.

Into the details of manufacture and composition we do not propose to enter. It will suffice to say that the composition of natural cements, even from the same place, varies considerably, and this, of course, is a disadvantage. They are burnt at a comparatively low temperature, otherwise they would fuse into glassy, useless lumps on account of the iron, &c., which they contain. After calcination, they contain a certain amount of uncombined lime, that is to say, calcium oxide, and also a small quantity of tricalcium silicate, which is, according to Le Chatelier, the most important ingredient of Portland cement: the bulk of the cement, however, consists probably of calcium aluminates, and it is this which differentiates them from Portland cement. The cement-stone, after calcination, will not slake on the addition of water, and is therefore ground between mill-stones; the powder is then packed into barrels or sacks, ready for use, and should be kept thoroughly dry, as it is very liable to deterioration from moisture. The finer the cement is ground the better will it be.

Weight.—The weight of a "striked" bushel of Roman or Medina cement is about 75 lbs. to 80 lbs., being therefore about 30 lbs. less than the same quantity of Portland cement.

Strength.—The strength of the different natural cements varies greatly, but the very best do not attain the strength

of good Portland cement. When tested neat, the superiority of the latter is not so marked, but the more sand is added, the greater does the disparity between the strength of the two kinds of cement become. So small indeed is the adhesive strength of Roman cement, that it is seldom mixed with more than its own bulk of sand.

TENSILE STRENGTH. — Table I. (page 20), gives the tensile strength of a Rugby Lias cement and of two Portland cements, and shews the superiority of the latter, and especially their superior sand-capacity. The Rugby Lias cement mortar (1 to 6) is 70 per cent. weaker than the 1 to 3 mortar, while with Portland cement the difference is only 43 per cent.; or, to put it another way, Portland cement is about twice as strong as the other when both are mixed with three parts of sand, but with six parts of sand it is nearly four times as strong. According to this table, the strength of briquettes kept in water is, at twelve months, considerably in excess of those kept in air. Table IV. shows the strength of other natural cement briquettes, at 28 days, to be less when kept in water than in air.

TABLE IV.*—STRENGTH OF ROMAN AND PORTLAND CEMENT MORTARS (1 Cement to 3 Sand) in lbs. per sq. inch.

Cement.	Measured by	Kept in	Tensile Strength.		Compressive Strength.		Ratio between Tensile and Compressive strength	
			7 days.	28 days.	7 days.	28 days.	7 days.	28 days.
Roman .	Weight	Water	40·5	121·5	300	882	1 – 7·4	1 – 7·3
,,	,,	Air	111·5	200	530	1149	1 – 4·8	1 – 5·7
Portland	,,	Water	211	273	1735	2690	1 – 8·3	1 – 9·8
,,	,,	Air	237	304	1860	2800	1 – 7·9	1 – 9·3
Roman .	Volume	Water	18·5	54·1	123	322	1 – 6·7	1 – 5·9
,,	,,	Air	58·2	94	178	488	1 – 3	1 – 5·2
Portland	,,	Water	203	265	1535	2490	1 – 7·6	1 – 9·4
,,	,,	Air	228	278	1715	2670	1 – 7·5	1 – 9·6

* The figures in this table are taken from the *Proc. Inst. C. E.*, vol. ciii. (1890–1) part i., but two or three evident misprints have been corrected.

Professor Dr. Boehme obtained the results as shown in Table IV. with Roman and Portland cements mixed with sand in the proportion of 1 to 3, some of the briquettes being kept in air and some in water.

One important point which these tests exhibit is the great difference in the strength of mixtures of Roman cement and sand, measured by weight and by volume. The difference with Portland cement is not so striking, because, bulk for bulk, the weight of Portland cement is not much different from that of sand; in this case, the proportion of 1 to 3 by weight was equal to 1 to 2·864 by volume. But with Roman cement the briquettes, proportioned by weight, are, on the average, exactly 60 per cent. weaker than those proportioned by volume. This difference is due to the heaviness of the sand in comparison with that of the cement; the briquettes measured by volume contain, therefore, considerably more sand in proportion than those measured by weight.

When we consider that in making briquettes, the ingredients are usually proportioned by *weight*, and in making concrete or mortar by *volume*, we see how easily an error may be made in calculating the probable strength of a structure. If tests of briquettes made by weight give a certain strength per square inch, and this strength be made the basis of calculation for the strength of concrete made by volume, the result may be disastrous, for the concrete may have less than half the strength which the calculations show it ought to possess.

A little arithmetic suffices to reduce the proportion by weight to the proportion by volume, provided that the weights of the cement and sand are known. If cement weighing 75 lbs. per bushel be mixed with sand weighing 100 lbs. per bushel in the proportion of 1 to 3 by weight, we should have 75 lbs. (= 1 bushel) of cement, and 225 lbs. (= 2·25 bushels), of sand, or a proportion of 1 to $2\frac{1}{4}$ by volume, which would be 20 per cent. stronger than 1 to 3 by volume.

The great strength of Portland cement in comparison

with the Roman is also plainly shown. If we take the briquettes proportioned by volume and set in air, these being the conditions usually obtaining in buildings, we find the tensile strength of Portland cement and Roman cement to be as 4 to 1 at seven days and 3 to 1 at twenty-eight days, and the compressive strength as nearly 10 to 1 at seven days and over 5 to 1 at twenty-eight days. These ratios show that the Portland cement, although it sets more slowly than the other, attains a greater proportion of its ultimate strength at seven days than does the Roman.

Other experiments by Mr. Grant extended over a period of seven years, and included tests of Portland, Roman and Medina cements. The results showed that, roughly speaking, the first two attained their full strength at the age of 2 years, and the last at the age of one year. After these periods the Portland cement remained stationary, the Roman cement increased a little (about 9 per cent.), while the Medina cement unaccountably lost nearly one-half its strength before the end of the second year, but in the succeeding five years gradually regained nearly one-half this loss. Portland cement mortar (1 to 1) was found to be considerably stronger than neat Roman or Medina cement. Neat Portland cement was stronger at 7 days than either of the other cements at any period.

Some interesting experiments with Portland cements and natural American cements were made by Prof. E. J. De Smedt (of Washington, U.S.A.), showing their gradual increase of strength from one day to twelve months; at ten days the Portland cements were about one-half the strength they attained at twelve months, and the natural cements about one-third.

ADHESIVE STRENGTH.—The adhesive strength of natural cement is only about one-half that of good Portland cement, both tested neat; and the advantage of Portland cement increases with increasing quantities of sand.

COMPRESSIVE STRENGTH.—Table IV. shows that the compressive strength of Roman cement mortar (1 to 3, proportioned by weight) at 28 days is only one-third that

of a similar Portland cement mortar, and that, when the ingredients are proportioned by volume, its strength is less than one-sixth that of the latter. Mr. Grant found that cubes of Portland cement concrete (1 cement to 6 gravel and sand) were, at the age of 12 months, five or six times as strong to resist compression as similar cubes of Rugby Lias cement concrete; when the concrete was composed of 1 cement to 10 gravel and sand, the Portland cement concrete was found to be nine times as strong as the other (see Table XXI., page 183). The ingredients in Mr. Grant's tests were proportioned by volume, and, as we have already shewn, this is not quite fair to the Lias cement; after making, however, full allowance for this, the balance remains largely in favour of the Portland cement.

Transverse Strength.—A test of the transverse strength of a Roman cement is given in Table XI. (p. 72).

Uses.—The advantages of Portland cement are so great that it has almost ousted Roman from the market. One reason why the natural cements continue in use is that they set in a few minutes, and can, therefore, be used in running water, where a slow-setting cement would probably be washed away before it had had time to set. Engineers sometimes make use of Roman cement, either alone or in combination with Portland, for exposed works in the sea, where rapidity of set is required. Such cements are also useful for bedding floor-tiles upon, and for other purposes where rapid setting is a necessity. This rapidity of setting, however, renders the cement difficult to use, and, in the hands of careless workmen, causes bad results. Only a little should be mixed at a time, and that must be used immediately, and must not be disturbed, either by ramming or in any other way, after it has been deposited in its place.

2. Plaster of Paris, &c.

Composition, &c.—Plaster of Paris is ground from the clinker obtained by burning gypsum at a temperature of

250 to 270 degrees Fahrenheit, until nearly the whole of the moisture in it has been expelled. Gypsum is a hydrated sulphate of lime ($Ca\,SO_4 + 2H_2O$); plaster of Paris contains only one-fourth the quantity of water, and is expressed thus, $2\,Ca\,SO_4 + H_2O$. On the addition of water to the plaster the particles are reconverted into gypsum, which dissolves in the water. When the latter becomes super-saturated, crystallization takes place, the gypsum being deposited in groups of fibre-like crystals. This setting process is very rapid, the plaster being "set hard" in a few minutes.

Plaster of Paris weighs about 64 lbs. per "striked" bushel, or one-third less than finely-ground Portland cement, and its strength likewise bears about the same ratio to that of the latter.

STRENGTH.—The average tensile strength of neat plaster of Paris briquettes, kept in air, was ascertained by Mr. Lockwood to be 355 lbs. per square inch, and of neat Portland cement briquettes 649 lbs. per square inch, all being made at the same time, and tested at the end of fourteen days. Some briquettes of plaster of Paris were immersed in water, but would not set there.

USES.—Plaster of Paris has been used in concrete, notably by Messrs. Dennett & Ingle, for fire-resisting floors and ceilings. It cannot be used for concrete in foundations or in water, or for concrete walls and stucco exposed to the atmosphere, as it is soluble in water. For floors and internal plastering, however, it can safely be used.

RESISTANCE TO FIRE.—It is often said that plaster of Paris resists the influence of fire more than any other cement, but we are of opinion that its fire-resisting properties have been much over-valued, and are inclined to think that it has no advantage in this respect over good Portland cement. A series of experiments has been carried out under the direction of Mr. J. J. Webster, M.I.C.E., which do not place it in a very favourable light. The results will be found in the *Proceedings of the Institution of Civil Engineers*, vol. cv. (1890–1, part iii.). Briquettes, having a breaking area of $2\frac{1}{4}$ square inches, were made of

various mixtures of plaster of Paris, with slag, fire-brick, and pumice-stone, and of Portland cement with the same and other aggregates. Ten briquettes of each kind were made, kept in air, and tested for tensile strength at the end of four or five weeks. Five of these were broken at the usual temperature of about 60 degrees Fahr. The other five "were carefully heated on the top of a specially built-up fire of coal and coke until they were of a light-red heat, the average time of exposure to the heat being about five minutes; they were then removed, and whilst hot were quenched with water. A large number of the briquettes lost all cohesive power after being quenched, and it was with difficulty that they were removed intact; as they could not in this state withstand any tensile strain, they were allowed to dry" for three days. They were then broken. A summary of the results is given in Table V., copied (with certain alterations) from Mr. Webster's paper.

This table needs some comment. In the first place, there are evidently several clerical or printers' errors in the table as printed in the *Proceedings*, for the average strengths of the briquettes given in the fifth and sixth columns do not tally in four cases with those calculated by the author from the individual tests, which are separately given by Mr. Webster. The only two, however, in which considerable variation occurs, are tests 8 and 11, column 6, where Mr. Webster has 39·06 and 6·9 instead of 30·06 and 4·7. But in the last column errors appear to have been made in calculation, and some of these were so great as to give quite a wrong idea of the relative value of the different mixtures; the author has therefore re-calculated the loss per cent. in all cases. The following are the figures given by Mr. Webster: 60·8, 80·0, 81·4, 79·8, 69·3, 50·9, 59·5, 57·1, 75·0, 94·7, 96·8, 90·0.

It ought also to be mentioned that out of the five briquettes of the several kinds, which were heated and quenched, one in No. 2 and one in No. 3 were "damaged before testing," three in No. 4 were "damaged before testing owing to their soft condition," one in No. 6 was "broken in adjusting in

TABLE V.—FIRE-RESISTANCE OF CONCRETE BRIQUETTES.

No.	Materials in Concrete Briquettes.	Proportions of Ingredients.	Average weight per cub. ft.	Tensile Strength per sq. in.		Average loss per cent. of original strength after Heating and Quenching.
				At Temp. of 60 deg. Fahr.	After being Heated and Quenched.	
			lbs.	lbs.	lbs.	
1	Portland cement	Neat	124·6	554·6	117·2	
2	" " and sand	1 to 1	120·9	448	93	78·9
3	" " "	1 " 3	111·2	100·8	18·7	79·2
4	" " "	1 " 5	109·7	74·6	15	81·4
5	" " iron-furnace slag	1 " 4	163·08	108·1	23·06	79·8
6	" " fire-brick	1 " 4	95·04	84·4	30·5	78·6
7	" " pumice-stone ...	1 " 4	64·8	94·6	38·3	63·8
8	" " coke-breeze	1 " 4	71·65	69·9	30·06	59·5
						57
9	Plaster of Paris and fire-brick......	1 " 4	89·6	66·8	10·3	84·5
10	" " pumice-stone ...	1 " 4	55·6	57·4	3·4	94·1
11	" " furnace-slag......	1 " 2	148	223·6	4·7	97·8
12	" " fire-brick	1 " 2	106·9	167·5	15·7	90·6

the machine," two in No. 9 were "too soft to be tested," and one in No. 10 and one in No. 11 were "damaged before testing." Of the briquettes tested in the ordinary way, two in No. 5, one in No. 6, one in No. 8, and one in No. 11 were "broken in adjusting in the machine," and another in No. 11 was "damaged before testing."

Mr. Webster has based his calculations on the strength of the briquettes which were actually tested in the machine, and has ignored the absolute lack of strength in those briquettes which were too soft to be tested, and the apparent weakness of those which were damaged before testing. We are not told whether the damages to these last resulted from being heated and quenched, or from accident at the hands of the operator, but it certainly seems only fair that those briquettes which were too soft to be tested ought to be reckoned. If we do this, we find that the briquettes of Portland cement and sand (1 to 5) have an average strength after heating and quenching of only 6 lbs., and the loss of strength will, therefore, appear as 91·9 per cent., and this is certainly more in accordance with what we should expect for briquettes containing such a large proportion of sand. If we apply the same method to the briquettes of plaster of Paris and firebrick (1 to 4), of which two were too soft to be tested, we get an average strength in column 6 of 6·2 lbs., and a loss, after heating and quenching, of 90·4 per cent.

More valuable results would have been obtained if the plaster of Paris had been tested neat, and also with coke-breeze and with sand, in exactly the same manner as the Portland cement was tested, but the tests are sufficient to show that concrete of Portland cement is not only originally stronger than that of plaster of Paris, but that it also withstands the deteriorating influence of fire and water better. The only tests which are strictly comparable are Nos. 6 and 7 on the one side, and Nos. 9 and 10 on the other. These show that briquettes of Portland cement and firebrick (1 to 4) are originally 26 per cent. stronger than similar ones of plaster of Paris and firebrick, while after heating and quench-

ing they are no less than 196 per cent. stronger, or, reckoning the two soft briquettes, 392 per cent. stronger. Tested with four parts of pumice-stone, Portland cement is originally 64 per cent. stronger, and after heating and quenching, it is actually 1,026 per cent. stronger than plaster of Paris. The average loss of strength caused by heating and quenching the Portland cement briquettes in the series Nos. 6 and 7, is 61·6 per cent., while the plaster briquettes in Nos. 9 and 10 lost 89·2 or (more correctly, we think) 92·2 per cent. The test, of course, was very severe, and concrete can hardly ever, in actual construction, be heated to such a degree and quenched so quickly, but it leads us to believe that Portland cement resists fire better than does plaster of Paris.

Mr. Hamor Lockwood made several blocks of concrete, some with gypsum and broken retorts (1 to 3), and others with Portland cement and burnt shale (1 to 4). At the age of six weeks they were all "subjected to intense heat for 1 hour and 45 minutes, after which they were plunged into water for 8 minutes, and when taken out those made with gypsum were completely disintegrated; whilst it took considerable force, applied with a sledge-hammer, to break those formed with Portland cement." These tests would have been more valuable if the nature and proportion of the aggregate had been the same in each case, but they certainly point to the truth of our contention, that the fire-resisting properties of plaster of Paris and allied cements have been greatly over-estimated.

Experiments were made about sixteen years ago by Mr. Thaddeus Hyatt,* "as to *the non-conducting power* of various substances, such as plaster of Paris of different densities, and concretes more or less porous, also air spaces; the result of all being that the best material to protect the metal against heat was found to be that which was strongest in compression, viz., Portland cement concrete of best quality,

* See "Experiments with Portland Cement Concrete combined with Iron," p. 21.

no advantage for any purpose being found from *fibres* of any kind, not even *asbestos.*"

This concurrent testimony in favour of the superior fire-resisting properties of Portland cement is a strange commentary on the oft-repeated praise of plaster of Paris, and leads us to think that a mere unsupported statement of opinion respecting the latter, has gradually come to be accepted as fact and has been quoted as fact so long that everybody has begun to believe it.

ROBINSON'S CEMENT.—Robinson's cement is, like plaster of Paris, a sulphate of lime. It is calcined from alabaster quarried at Knothill, near Carlisle, and is used not only for plastering, but also for concrete. The same statements are made about its fire-resisting qualities as are made about plaster of Paris; but no results of comparative tests made between it and other cements, are given by the manufacturers in proof of these statements, and until we receive such results, we must conclude that the cement is no better in this respect than plaster of Paris.

The strength of a sample of the cement was tested by Mr. Henry Faija in 1885, and excellent results were obtained, as shown by the following table:—

TABLE VI.—TENSILE STRENGTH OF ROBINSON'S CEMENT, IN LBS. PER SQ. IN.

Ingredients.	Proportions.	At 3 days.	At 7 days.	At 28 days.
		lbs.	lbs.	lbs.
Cement	Neat	497	549	784
,, and sand...	1 to 2	—	459	525
,, ,,	1 to 4	—	297	331

The figures are each the average of five tests, and show the cement to be equal in tensile strength to the best Portland cement.

The resistance to crushing of neat Robinson's cement was found by Mr. Faija ~~to be "3,761~~ lbs. per cubic inch" at

the age of five weeks, the average of five tests being taken. The compressive strength is about 18 per cent. less than that of Portland cement tested in a similar manner by the same engineer but not at the same time.

It is said that the cement is slow-setting and easy to work; that it may be used for an hour and a half after being gauged without detriment to its ultimate strength, and that in setting it "neither expands nor shrinks." As we all know, plaster of Paris expands somewhat in setting.

CHAPTER IV.

MATRICES—(*continued*).

III. Artificial Cements :—1. Parian cement, Keene's cement, Martin's cement—2. Slag cement (Table VII.).

III.—ARTIFICIAL CEMENTS.

1. Parian Cement, &c.

Parian Cement, Keene's Cement, and Martin's Cement are artificial cements, which consist of plaster of Paris re-calcined in combination with alum, borax, and pearl-ash respectively. They possess considerable tensile strength when used neat, but have only a small capacity for sand. They are, like plaster of Paris, unsuitable for use in water or damp exposed situations, on account of their solubility. It would be possible to use them in concrete floors and ceilings, but on account of the additional cost of manufacture, they would have really no advantage for these purposes over plaster of Paris. These cements are, how ever, largely used for internal plastering, especially where the walls are to be painted ; they set rapidly, attain a hard surface, and will take a considerable polish.

2. Slag Cement.

A somewhat curious instance of the utilisation of waste-products is found in the manufacture of cement from iron furnace slag. For a number of years experiments were made to this end, but without much success, the chief difficulty being that of pulverising the slag to a sufficient degree of fineness. The hardness of the slag played havoc with the grinding-machines.

Composition.—All slags are not adapted for conversion into cement, as some contain substances which would prove injurious in cement, or do not contain the necessary ingredients in proper proportions. A suitable slag may contain about 36 per cent. of lime, 30 per cent. of silica, and 23 per cent. of alumina. If to this slag 30 per cent. of slaked fat lime were added, we should have a mixture containing 46·5 per cent. of lime, 25 per cent. of silica, 19 per cent. of alumina, and 9·5 per cent. of iron and other substances. This is actually the approximate composition of one slag cement, and differs from the composition of Portland cement in one or two particulars, notably in having from 11 to 14 per cent. less lime and about double the quantity of alumina. In some slag cements the proportion of lime is about 50 per cent. of the whole. Sometimes the slag contains an excessive amount of sulphur, and the cement made from it is of dangerous quality.

Manufacture.—Until recently, experimenters re-calcined the slag with the lime which had been added to it, but Messrs. Bosse & Walters a few years ago introduced a new process which seems to promise success. It was fully described by Mr. Gilbert R. Redgrave, A.M.I.C.E., in a paper which will be found in the *Proceedings of the Institution of Civil Engineers*, vol. cv. (1890–1, part iii.), and to this paper the author acknowledges his indebtedness for most of the information given in this chapter.

"The slag, on issuing from the furnace," says Mr. Redgrave, "is passed though a stream of water, by which means it is mechanically reduced to a spongy and readily-crushed material." The slag sand obtained from this is dried and ground to a fine powder between ordinary millstones. To this powder is added the requisite quantity (about 25 or 30 per cent.) of pure lime, which has previously been thoroughly slaked, screened, and dried. The mixture is then introduced into a machine called a "homogenizer," where it is more intimately mixed and more finely ground in a revolving drum partly filled with small iron or steel balls. In about an hour the cement is withdrawn, and ought to be ready for

at once, for as the lime which is not in combina-
ı ought all to have been thoroughly slaked and screened, slaking should not be necessary. The colour of the ıent varies according to that of the slag from which it is le, but it is usually lighter than Portland cement, on ount of the slaked lime which it contains.

Slag cement is usually slow-setting, requiring from two five hours before it resists a moderate pressure of the mb-nail. "When made up neat, it is more plastic and tuous than Portland cement, and yields a richer and er mortar."

Tests.—The same kinds of tests ought to be applied to ; cement as to Portland, namely, fineness, tensile strength, cific gravity, and perhaps weight. The soundness test may be applied, for it is possible for a slag cement to ow."

Weight.—The weight may be as little as 85 lbs. per ked bushel, and seldom exceeds 95 lbs., or over 15 per t. less than ordinary Portland cement. Probably the ll weight of slag cement is due chiefly to its extreme ness, as there are instances of Portland cement as narily ground, weighing 115 lbs. per bushel, while the e cement, ground extremely fine, weighed only 90 lbs. bushel.

Fineness.—On the importance of fine-grinding we shall dilate here. Suffice it to say that fineness, especially lag cement, is of extreme importance. Mr. Redgrave ares that slag cement ought to leave no residue at all on o. 75 sieve (5,625 meshes to the square inch), and not e than 15 to 20 per cent. on a No. 180 sieve (32,400 hes to the square inch). Now and then Portland ent has been tested, which has shown a degree of fine- s equal to the standard here demanded for slag cement, as a rule, 10 per cent. residue on a No. 50 sieve is sidered a fair test for Portland cement. A sample of cement tested at the Royal Testing establishment at in, in December, 1886, left no residue at all on a sieve ı 1,160 meshes to the square inch, only 1 per cent. on

one with 3,870, 5 per cent. on one with 5,800, and 14 per cent. on one with 32,200 meshes, but this, it must be remembered, was a manufacturer's sample.

TENSILE STRENGTH.—Good slag cement tested neat, is as strong as neat Portland cement, but, according to Mr. Redgrave, it gives considerably better results than the latter when both are tested with three parts of sand. The tensile strength of the cement, mentioned in the last paragraph, was ascertained at Berlin to be as follows :—

TABLE VII.—TENSILE STRENGTH OF SLAG CEMENT, IN LBS. PER SQ. IN.

	At 7 days.	At 28 days.
Slag cement, neat........................	647	692
„ „ and sand (1 to 3)	427	509

Each result is the average of ten briquettes, which were kept in air for twenty-four hours after gauging, being covered with writing-paper to retain the moisture, and were then kept in water for the rest of the time. The strength of the sand briquettes is exceedingly great, and is equal to that of some Portland cements tested neat; the German standard for Portland cement requires a tensile strength of 227·6 lbs. per square inch, tested with three parts of sand at twenty-eight days, and the highest tensile strength of Portland cement so tested, which has come under our observation, is 10 per cent. less than that of the slag cement as recorded above. It must not, however, be imagined that all slag cements give equally good results; we must not generalise from particular instances.

No tests of the adhesive strength of slag cement have, as far as we know, yet been made, but its capacity for sand shows that this must be very high.

COMPRESSIVE STRENGTH.—Briquettes of slag cement, mixed with three parts of sand, were made at Berlin as already described, and were crushed, on an average, by a

force of 3,376 lbs. per square inch at seven days, and 4,296 lbs. at twenty-eight days. Briquettes of Portland cement and sand, similarly tested by Messrs. Dyckerhoff, had an average strength of 4,822 lbs. at 28 days, or 12 per cent. more than the slag cement ones.

USES.—It can be used in all situations for which Portland cement is adapted, and has been employed in the construction of harbours and other works in the sea, as at Skinningrove, in North-East Yorkshire, and other places. For stucco and plastering and for concrete generally it is suitable. It has been used also for paving, but, according to Mr. Redgrave, it does not attain as hard a surface as Portland cement; its superior adhesive strength, however, enables it to bind the hard aggregate of the paving, such as granite and quartz "into a firmer mass than Portland cement does." Mr. G. M. Lawford* states that its fire-resisting properties "exceed those of both gypsum and Portland cement," and for this reason, among others, it can be recommended for use in concrete floors and roofs, &c.

* In paper on "Fire-proof Floors," read before the *Society of Engineers*, April, 1889.

CHAPTER V.

MATRICES—(*continued*).

III. ARTIFICIAL CEMENTS (*continued*):—3. Portland cement—History—Raw materials—Manufacture—Composition—Necessity of testing—Test-specialists—Tests: Weight, Specific gravity (Table VIII.), Fineness.

HISTORY.—Undoubtedly the most valuable matrix for concrete is Portland cement. Strength for strength it is cheaper than lime. By its aid works have been executed which seem able to withstand for ages the rough usage of stormy seas and the insidious attacks of the atmosphere. It is first mentioned in a patent granted to Joseph Aspdin, a bricklayer of Leeds, in 1824, that is to say, nearly thirty years after the introduction of Roman cement by Parker. The name "Portland" was given to it in consequence of a resemblance of its colour to that of Portland stone. Aspdin's cement was a mixture of pulverised quick-lime and clay, but neither the mode of manufacture nor the nature of the cement is identical with modern practice. In 1825 he established a manufactory at Wakefield, in Yorkshire, and in a few years his son William, in partnership with one or two other persons, began to make Portland cement at Northfleet, on the Thames. Mr. I. C. Johnson was of opinion that he himself was the first maker of true Portland cement; in 1844 he introduced its manufacture into the works of Messrs. J. B. White & Co. However this may be, there is no doubt that, soon after this time, Portland cement began to be better appreciated. Its value was ascertained by actual use and by numerous tests, such as those carried out by Mr. John Grant, from 1859 almost to the present time;

and to-day it is employed for engineering works the world over. It has been estimated by an American writer, Mr. Giron, that the present annual production of Portland cement is more than 20,000,000 barrels, and that of these about 8,300,000 barrels are made in England. To engineers chiefly we must look for information respecting this material, and to them architects and builders owe a debt of gratitude.

Raw Materials.—The raw materials from which Portland cement is manufactured vary to a considerable extent. On the Thames and Medway, chalk and river-mud or clay are the constituents; while at Rugby, Stockton, &c., in Warwickshire, at Poole in Dorset, and at various places in Somerset, Nottinghamshire, Lincolnshire, &c., Blue Lias limestone and shale are used. The aim of the manufacturer is to obtain a mixture of clay and lime in which the carbonate of lime before calcination shall be from 74 to 77 per cent. of the whole. When chalk, which is nearly pure carbonate of lime, is used, it is comparatively easy to obtain the requisite proportion of lime to clay, but when a limestone consisting partly of clay and partly of carbonate of lime, as Lias limestone does, is used, more difficulty is experienced, for the composition of limestone is subject to considerable variations. In any case frequent analyses of the materials are necessary.

An excess of clay in the composition produces a cement of less strength and weight than usual, and liable after setting to crumble away on exposure to the atmosphere; such cement, when mixed neat with water and left in the air, will have a buff colour. Over-clayed compounds are liable to fuse in burning, and, as this would render the clinker useless for cement purposes, they are burnt at lower temperatures, and produce cements which partake somewhat of the character of Roman cements. An excess of lime has also disadvantages, for it may produce a cement containing more or less caustic lime, and having therefore a tendency to crack or "blow" when made into mortar or concrete; this danger may be lessened by burning the clinker at a high tempera-

ture, by grinding the cement very fine, and by properly purging or air-slaking the cement before it is used.

MANUFACTURE.—In the "wet" method of making cement, the lime and clay are mixed in proper proportion, and broken up with water in a wash-mill, which is usually a pit forming a ring around a central pier; on this pier a vertical shaft fitted with horizontal arms revolves, and from the arms knives or cutters descend almost to the bottom of the pit; other arrangements, however, are often adopted. Originally the volume of water exceeded that of the chalk and clay with which it is mixed, and this necessitated the conveyance of the wet "slip" into "backs" or reservoirs, where it remained for a month or more until sufficient water had evaporated or drained away from it. Besides other disadvantages, this system entailed extensive areas of ground for "backs," and also great delay. In 1870 a new method of manufacture was patented by Goreham, the chalk and clay being mixed in the wash-mill with about one-third their volume of water, the slip thus formed being passed immediately between horizontal mill-stones, by which it was well ground; from the mill-stones the slip was conveyed (by pumps or otherwise) direct to the drying-floors, instead of to the "backs." In the more modern "dry" process, the materials are ground and mixed without water, and then slightly moistened and pressed into "bricks" of a convenient size for burning in the kiln.

Originally the "slurry," or wet slip, was dried on floors heated by coke ovens; but, in new works, where the wet process is adopted, the waste heat from the kilns is utilised for heating the drying-floors, and by this means a considerable saving is effected. From these floors the dried slip is broken and put into the kiln and burnt at a high temperature, the object being to produce a hard, well-burnt, but not vitrified "clinker." It is, of course, impossible to obtain a perfectly-uniform clinker, but in this respect the dry process is superior to the wet, on account of the uniform size of the "bricks." Some portions of the clinker will be over-burnt,—these, if ground would have no cementi-

tious value; other portions will be of a clayey hue, and decidedly under-burnt—these would produce a dangerous cement, liable to crumble away after exposure to the atmosphere. The former should be thrown away as waste, while the latter may be placed on the top of the next kiln and reburnt. Very cheap cement will probably prove to have been ground from under-burnt clinker, as this is more easily ground than heavily-burnt clinker. The latter, however, should be used, as it yields a cement considerably stronger than a lightly-burnt cement, when ground to the same degree of fineness.

The properly-burnt clinker is broken into small pieces by rollers, or Blake's stone-breakers, or other machines, and these pieces are then finely ground between grooved mill-stones, or in the more modern ball-mill and tube-mill. The resulting cement, particularly when ground by millstones, may contain many particles too coarse to be of any value; it is, therefore, by many manufacturers sifted by fine sieves, the particles remaining on the sieves being returned to the mill-stones, and ground with the next batch of broken clinker. These coarse grains, although in their coarse state they have no cementitious value, may prove, if finely ground, to be of excellent quality.

After leaving the mill-stones or mills, the cement in some factories is spread daily in a thin layer on the floors of store-rooms or warehouses, until several layers, representing a week's manufacture or more, have been distributed one above the other. Sometimes the cement is turned over occasionally. It is afterwards filled into sacks or casks, the different layers being as far as possible mixed in the operation. The cement is then ready for its destination, but not always for use. Of the precautions to be taken before using cement fresh from the manufacturer we shall speak hereafter.

In America a novel process of cement-manufacture has been adopted; the raw compound is burnt, we are told, "in a powdered condition, while travelling in an inclined rotary furnace in an intensely hot petroleum flame, and a few hours is sufficient to finish the process." Apparently

the invention is a successful one, for the cement is guaranteed to bear without breaking a tensile stress of 400 lbs. per square inch after seven days, 500 lbs. after twenty-eight days, and 600 lbs. after three months, and to leave no more than 10 per cent. residue on a sieve with 6,400 meshes to the square inch.

Composition.—Roughly speaking, Portland cement contains about 62 per cent. of lime, 22 per cent. of silica, and 7 per cent. of alumina; the remaining constituents being the alkalies,—soda and potash,—oxide of iron, magnesia, sulphuric acid, carbonic acid, &c. To the user of cement, its detailed composition is not of primary importance; the chief points for his consideration are the strength and durability of the cement, and one cement must not be condemned because it differs slightly in composition from another of established reputation; for instance, the lime in different cements varies from, say, 56 to 65 per cent. of the whole. A wide difference, however, calls for considerable caution and careful tests. Dr. Michaëlis says that the extreme limits of variation which can be allowed in Portland cement are, for silica, from 19 to 25 per cent.; for alumina from 4 to 9 per cent.; and for ferric oxide, from 2 to 5 per cent. Analyses of several Portland cements will be found in Table XII, p. 89, and the parts played by the various ingredients in the setting of cement are discussed in the same chapter.

Necessity of Testing.—The necessity of testing Portland cement before using it in important works is recognised by all engineers, and ought to be recognised by all architects. It may be argued that, if the cement be obtained from a firm enjoying a good reputation, there is no need for tests. There is, perhaps, less need for them, but they ought not to be altogether omitted. In this day of advertisement, it is often difficult to ascertain whether a reputation is founded on good manufacture or on advertisements; and even if the cement from a reliable manufactory has been specified, there is a possibility that another kind may be used instead.

Another argument that may be advanced is that the contractor is responsible for failures in material, and that, if by using inferior cement the concrete should fail, he will have to do the work again at his own cost; therefore the *onus* of testing, it may be said, rests upon him. A moment's consideration will show how unfair to the building-owner is such a view of the case; for the building-owner may have to bear the loss by delay consequent on the failure of the cement, or may be able to recover damages only after an anxious law-suit. Again, there is a grave danger that the bad character of the cement may not discover itself until some months have elapsed, perhaps not until the architect's final certificate has been granted, and, in the latter case, there will probably be trouble for architect and contractor, as well as for the building-owner; and further, a cement may be used which produces concrete sufficiently good to escape condemnation, but which is far from being the best which could have been obtained under the terms of the specification, and in this case the building-owner is decidedly the loser because proper tests were not carried out.

When we think of the important uses to which concrete is put in our buildings,—as, for instance, foundations and floors,—we cannot fail to see the necessity of knowing the character of the cement, which is its most important ingredient. To specify that "the best heavy Portland cement" must be used is not enough, but such a description is far from uncommon. Quite recently a case came under the author's notice in which the concrete for an engine-bed was specified to be of cement, vaguely described as in the last sentence, and of broken stone, &c., in the proportion of one to four,—a proportion of cement to aggregate which ought to insure an excellent concrete; but what happened? The concrete was deposited and set properly; after a month, however, it began to show signs of disintegration, and it gradually crumbled until the architects had to order its removal; the contractors removed it and laid a new foundation, and on the completion of the whole building claimed an "extra" for the work. The

architects refused to allow the claim, but, believing that the contractors had not wilfully used inferior material, they asked the building-owner to deal "generously" with the unfortunate builders. Altogether a very pretty muddle, and one which probably would have been avoided if the cement had been submitted to one or two comparatively simple tests. Many instances of the failure of concrete have occurred, which might have been prevented by a judicious testing of the cement.

TEST-SPECIALISTS.—We do not mean to say that architects must fit up a part of their offices as testing-laboratories, and themselves become proficient in the art of making and breaking briquettes, &c. No, architects have quite enough on their hands without taking up another burden. The necessary appliances for testing are many and somewhat costly, and the testing itself is no easy matter. But this is an age of specialists, and cement-testing, like so many other matters, is becoming the special study of certain engineers.

For large works, a clause might be inserted in the specification to the effect that the contractor must include a certain sum for cement-testing, the tests to be carried out by a specified person, or by one to be approved by the architect. For small works, the cement might be specified to be obtained from a particular maker, and the architect or the clerk of works could easily test the cement as to its "soundness," taking its fineness and strength for granted.

TESTS.—The tests now considered of primary importance are those for ascertaining the *fineness*, *tensile strength*, and *soundness* of the cement. The *specific gravity* is also thought by many to be of importance; but the *weight*, which at one time was considered the most notable characteristic (perhaps because it could be ascertained with comparative ease), does not now command very much attention, and is only considered in connection with the fineness and specific gravity. Some years ago a vague specification would have required "the best *heavy* Portland cement;" to-day the description would probably be altered to "the best *finely-ground* Portland cement," provided, of course, that the author of such

a vague description as the first could be induced to make any alteration at all.

Several other tests have at various times been adopted, such as those made to ascertain the relative hardness of different cements, their resistance to transverse and crushing stresses, and their adhesive strength; these have their uses, but are seldom specified in England.

COLOUR.—The colour of cement affords little evidence of its quality, as in many instances it is due mainly to the presence of iron. Sometimes, however, a yellowish hue is the result of under-burning, and if that be the case, the cement will prove comparatively weak, and may be unsound. As a rule, good Portland cement is of a bluish-grey or dark-grey colour, and is soft to the touch. Quick-setting cement has often a brownish tint.

MICROSCOPIC EXAMINATION.—It is probable that in the near future a microscopic examination of Portland cement will be almost, if not altogether, sufficient to enable the observer to judge of its value; the researches of Mr. Alden H. Brown, of the University of Iowa, seem, at any rate, to point to this conclusion, but sufficient observations and experiments have not yet been made to obtain absolute proof of this.

SAMPLING.—When it is desired to test a consignment of cement, a small quantity should be taken from each of several casks or bags immediately on their arrival, care being observed that the cement is not taken from the outermost portion in the cask or bag, but from the interior. If the test is to be made by some one at a distance from the works, the sample should be carefully packed and sent as soon as possible. As a rule, not more than 28 lbs. of cement will be required for testing.

WEIGHT.—The weight of Portland cement is stated in a well-known book to vary from 95 lbs. to about 130 lbs. per "striked" bushel. To-day manufacturers produce cements apparently more uniform in weight than these figures show. The chief causes of this smaller difference are the better knowledge which is now possessed of the ingredients of

good cement, the more uniform degree of fineness to which it is ground, and also the greater care with which the weight is ascertained. The method of filling the measure has much to do with the apparent weight; it may be filled very lightly by allowing the cement to fall down a short shoot of easy slope, or may be more closely filled if the cement drop vertically into it from some height; or, still more compactly, if the measure be shaken during the filling.

The necessity for some uniform and satisfactory method of ascertaining the weight has long been recognised, and various devices have been adopted for this purpose. In some cases the measure is filled from a short shoot, down which the cement slips at a moderate velocity. In others, the cement is put into a coarse sieve, from which it drops into a measure placed, say, 3 ft. below it. Mr. Henry Faija, M. Inst. C. E., has devised an apparatus which ensures uniformity of filling; the cement is placed in a hopper, from the bottom of which it passes into a trough; on turning a handle a worm in this trough revolves and gradually conveys the cement forward to an opening, whence it drops directly into the measure below. When the measure is piled full, the cement is struck off level by means of a straight-edge and then weighed; the weight of the measure itself, which has previously been ascertained, is deducted from the total, and the balance is the weight of the cement contained in the measure.

Sometimes the measure in which the cement is weighed contains only part of a bushel, and this is another cause of discrepancy, for in a larger measure the cement is more compressed than in a smaller one, and the weight therefore appears greater. Mr. John Grant ascertained that 10·75 measures, each containing one-tenth of a bushel, were required to fill one bushel measure. In other words, if the weight per bushel were 107·5 lbs., the weight per tenth of a bushel would be only 10 lbs., which, multiplied by ten, would give an apparent weight per bushel of 100 lbs., a difference of 7½ per cent.

The freshness of the cement has also a considerable influence on the weight. It has long been known that the storing of cement increases its bulk without corresponding increase of weight. This is due to the slaking, by the moisture of the atmosphere, of the quicklime or calcium oxide contained in the cement, and its conversion into the more bulky hydrate of lime. Therefore, the more thoroughly slaked the cement is, the less does it weigh per bushel. Some cements, of course, show considerably more increase in volume and decrease in weight per bushel than others. Experiments by Mr. Faija, disclosed to the *Society of Engineers* in 1888, showed that a cement which just after grinding weighed 120 lbs. per bushel, might when a few days old weigh only 114 lbs., when six months old 100 lbs., and at the end of a year not more than 95 lbs. per bushel.

The weight of cement varies also according to its fineness. The finest cement, other things being equal, weighs the least. Mr. John Grant gives the weights of seven varieties, unsifted, and sifted through a sieve with 2,304 meshes per square inch. The average weight of the unsifted cements was 11·04 lbs. per tenth of a bushel, while the siftings weighed only 9·54 lbs. for the same quantity,—a decrease of more than 13·6 per cent., or about 16 lbs. per bushel. Dr. Michaëlis instances one excellent cement, which, as ordinarily ground, weighed 90 lbs. per cubic foot (about 115 lbs. per bushel), but which, when ground so that all passed a sieve with 32,000 meshes per square inch, weighed only 70 lbs. per cubic foot, or about 90 lbs. per bushel.

A higher degree of calcination yields a heavier cement, and the composition of the cement also affects the weight.

From this evidence it is clear that the weight of a cement, taken by itself, is no criterion of the cement's value. A heavy cement may be fresh, and coarsely-ground; on the contrary, it may be well-burnt. A light cement may be under-burnt; on the contrary, it may be free from unslaked lime, and finely-ground. Both may give equally good or bad results as to strength and stability. The weight is valuable only when taken in connection with other par-

ticulars, but the best Portland cements, when received from the manufacturers, will usually be found to weigh within 5 per cent. (more or less) of 112 lbs. per bushel.

Specific Gravity.—Among engineers there has been, of late years, a growing idea of the importance of ascertaining the specific gravity of cement. Mr. Grant in 1879–80 thought it was not of much practical benefit; the specific gravity of thirty or forty cements, which he had tested, only ranged from 3·193 to 3·040, the extreme variation being, therefore, less than 5 per cent. Other experimenters have found greater variation, the specific gravity in some cases being as low as 2·77. Mr. Faija, in his valuable little book, "Portland Cement for Users," gives a table of the testing of fifteen samples of cement; from which we extract the figures relating to two samples, almost identical in weight, specific gravity, and fineness, but differing exceedingly in strength and hydraulic activity.

Table VIII.—Variableness of Portland Cement.

	Weight per striked bushel.	Specific gravity.	Residue per cent. after sifting through sieves, Nos. *			Broke at lbs. per sq. in. of section at —days from gauging.			Nature
No.	lbs.	—	25	50	75	7	28	182	
3	111	2·89	½	21	32	510	647	772	Quick-setting.
10	110	2·90	1	21	31	332	401	460	Slow- „

The tensile strength in each case is the average of ten briquettes, which were kept in water from the time of gauging. The table is interesting as showing that Portland cement must not be judged either by its weight, specific gravity, or fineness, or even by these three particulars taken together, but must be actually made into briquettes and broken before its character can be determined.

Mr. Faija considers that the specific gravity should never

* Cement-sieves are known by the number of meshes per lineal inch; thus, a No. 25 sieve has 25 meshes per lin. in. or (25 × 25 =) 625 per sq. in., and a No. 50 sieve has (50 × 50 =) 2500 meshes per sq. in.

be less than 2·92, but other authorities hold that cement a month old should have a specific gravity of 3·1 to 3·15. A high specific gravity, combined with extreme fineness, indicates that the cement is well burnt. A specific gravity of less than 2·9 indicates an under-burnt or stale cement.

Fineness.—The importance of fine-grinding is now universally conceded, as it has been demonstrated that only the finely-ground portion of cement has any considerable cementitious value. The coarse particles of cement are apparently of two kinds—the first consisting of those impure or hard-burnt grains on which water has no effect, and which are consequently as worthless as so many grains of sand, and the second consisting of useful material, not sufficiently triturated, and therefore extremely sluggish in its action. The effect of the former on the setting of the cement is simple, while that of the latter is complex and not yet thoroughly understood. The usually-accepted theory is that the coarse particles of the second kind partake of the nature of hydraulic limes, and exhibit a certain amount of slaking action some time after having been mixed with water. As we have already seen, the slaking of lime is invariably accompanied by increase of bulk, and this has the effect of disintegrating to some extent the remaining portion of the cement which has already set. Many failures of concrete have been attributed to this cause.

These coarse particles of lime will gradually slake if the cement be exposed to the atmosphere, and it is to accomplish this end, that Portland cement is usually stored in bulk for some weeks before use. The fact, that the storing of cement results in the hydration of coarse grains, is shown by the increased bulk of the stored cement and by its diminished weight per bushel. Fine cement does not require "air-slaking" to the same extent as coarse.

Some of the inert hard-burnt grains already mentioned would doubtless yield, if finely ground, an energetic cement; but in their coarse state they are not acted upon by water and are consequently an adulterant, like sand.

From many tests made with different cements by

different operators, Mr. Grant learnt the apparently curious fact that briquettes composed of a certain quantity of Portland cement and three times its weight of sand, were not as strong as briquettes made with the same quantity of sand and only that portion of the original quantity of cement which would pass through a sieve of 5,806 meshes to the sq. in. Thus,—taking a cement which leaves 10 per cent. residue on such a sieve,—we have, in the first case, the proportion of cement to sand as 1 is to 3, but in the second case the proportion becomes as $\frac{90}{100}$ is to 3, or as 1 is to 3·3, and yet the latter yields the stronger mortar. This simply means that the coarse cement is practically inert, and should be considered as so much sand; if this be done, the ratio between the energetic part of the cement, and the sand *plus* the inert part of the cement, will be found to be as 1 is to 3·4,—thus, $(1 - \cdot 1) : (3 + \cdot 1) :: 1 : 3\cdot 4$,—and this mortar is evidently inferior to that from which the coarse particles of the cement had been excluded.

Cements containing coarse particles have sometimes (but not invariably) a higher tensile strength than the siftings of the same cements, when all are tested neat; but when all are tested with three or more volumes of sand, the finer cement invariably gives the better results. Among many experiments in proof of this we may instance those of Messrs. Dyckerhoff, which showed that a cement which left 10·2 per cent. on a sieve with 2,580 meshes per sq. in., and 18·8 per cent. on one with 5,806, was at the age of 25 weeks, 41 per cent. *stronger* than the siftings which had passed a sieve with 32,200 meshes per sq. in., both being tested neat; but, when both were tested with three parts of standard sand, the briquettes made with unsifted cement were 29 per cent. *weaker* than those made with the siftings.

Even, however, if the siftings of a cement are stronger than the original cement when both are tested neat, the increase of strength is much more marked when both are tested with sand. Mr. H. K. G. Bamber* experimented with

* "Portland Cement: The value of fine grinding," a paper read before the *Incorporated Association of Municipal and County*

a cement which left 15 per cent. residue on a No. 50 sieve. The *neat siftings* through a No. 50 sieve (A) were found to be 6 per cent. stronger than the original at 7 days, the siftings through a No. 70 sieve (B) 9 per cent. stronger, through a No. 90 sieve (C) 13 per cent., and through a No. 110 sieve (D) 16 per cent. stronger. When, however, all were tested with 3 parts of sand (by weight), at the age of 28 days A was found to be 20 per cent. stronger than the original cement, B 37 per cent., C 53 per cent., and D no less than 90 per cent.

Dr. Michaëlis asserts that if a cement, which has all passed through a No. 40 sieve, be sifted through a No. 75 the particles remaining on the latter will be "absolutely valueless" as a cementitious agent. Mr. Gustav Grawitz, as long ago as 1880, said that the principal authorities in Germany agreed that the residue on a sieve of 5,806 meshes per sq. in. was "entirely worthless, had no cementitious power whatever, and might—and undoubtedly did in certain cases—prove a source of danger." Recent experiments by Baron Quinette, at Havre, showed that the residue on a sieve with 2,100 meshes per sq. in., had an average tensile strength of only 13 lbs. per sq. in. at 4 months, 43 at 9 months, and 76 at 18. If this residue is not "entirely worthless," we must admit that it is very nearly so.

The degree of fineness to which cement ought to be ground is a matter of controversy even yet, but ever since the advantages of fine grinding were recognised, the tendency has gradually been to increase the stringency of specifications, so that a cement, which at one time was considered fine, would to-day be considered coarse.

Not very long ago sieves Nos. 30 or 40 were frequently specified, but these have been abandoned in favour of finer ones. A No. 50 sieve is still much used, not more than 10 per cent. of the cement to be retained by it. Mr. H. K. Bamber, F.I.C., in November, 1891, insisted that cement should be so fine that all would pass through a

Engineers, July 14, 1893, and reported in *The Building News*, for July 28, 1893.

No. 50 sieve, and not more than 10 per cent. be retained by a No. 75 sieve. This is nearly the same as required by the German and Austrian standard regulations; but in Germany, we are told, cements can be obtained which leave less than 10 per cent. on a sieve with 32,200 meshes per sq. in.

Mr. Colson advocates (and wisely, we think) that *all* the cement, and not a certain proportion of it, should pass the specified sieve.

For practical purposes, the degree of fineness will be regulated by a comparison between the cost of fine grinding and the resultant increase in strength; up to a certain limit, the advantage of fine grinding increases in a greater proportion than the cost, but beyond that limit, the proportion is reversed, and, to attain a given strength of concrete, it would become more expensive to use the extremely fine cement than a proportionately larger quantity of somewhat coarser cement.

It has now been proved that, by modern methods, cement can be profitably manufactured which will leave no residue on a No. 50 sieve, and not more than 2 per cent. on a No. 76, or 5 per cent. on a No. 100. Other things being equal, a fine cement is stronger than a coarse one, sets more quickly, and is less liable to expand or "blow" in setting.

The standard sieve in the United States and in the principal European countries is formed with wires of a thickness equal to half the width of the meshes,—thus, a No. 50 sieve has wires ·0068 inch thick and openings ·0132 inch wide, and a No. 76 has wires ·0044 inch in diameter and openings ·0087 inch wide. Unfortunately this simple standard has not yet been generally adopted in England; in the principal Government Departments the wire for a No. 50 sieve is ·007 inch, and that for a No. 76 is ·005 inch, and the maximum residue allowed on the former sieve is 2 per cent. and on the latter 10 per cent.

Sometimes the amount of "flour" in a cement is ascertained by means of a flourometer, but this test is not often specified. In a good cement the flour will be nearly 60 per cent.

CHAPTER VI.

MATRICES—(*continued*).

III. ARTIFICIAL CEMENTS (*continued*) :—3. Portland cement (*continued*)—Strength : *Tensile*, Briquettes, Water (Table IX.), *Compressive* (Table X.), *Transverse* (Table XI.), *Adhesive*—Increase of strength and durability.

TENSILE STRENGTH.—The test for tensile strength is one of the most important which we have to consider, and in this, again, very different results may be obtained by different operators and with different apparatus. The temperature, the amount of water, the rate at which the strain is applied, all affect the result. The results vary also to the extent of 30 per cent. or more, according to the testing-machine used, and they are largely influenced by the form of the briquette, and of the clips by which it is held in the machine.

SHAPE OF BRIQUETTES.—Mr. E. A. Bernays, in 1880, gave to the *Institution of Civil Engineers* the results of tests he had made on four different forms of briquettes, all being of the same size at the neck or place where fracture would occur,—that is to say, $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in., or $2\frac{1}{4}$ square inches. Six briquettes of each form were made of "the same quality of cement," and tested at the end of seven days. The average tensile strength of briquettes of the form A was 602 lbs., B 760 lbs., and C 900 lbs., the last, therefore, giving results 50 per cent. higher than the first, and nearly 20 per cent. higher than the second

Form A is the form of briquette first used in testing cement, Form B is one of the many modifications which have been tried, and Form C is the one introduced by Mr. John

Grant, of the late Metropolitan Board of Works, and now generally adopted in England. Mr. Faija, however, has slightly altered the form by making each end of the briquette angular (like a gabled roof) instead of flat (see Fig. 2); this is done, not for the purpose of obtaining higher results, but for convenience in detaching the moulds in which the briquettes are formed.

The most usual size of briquette, at the smallest part or "neck," has been until recently, $1\frac{1}{2}$ in. square, or $2\frac{1}{4}$ square inches, but there are now a great many persons who advocate and use briquettes measuring only 1 in. square in the smallest part, and these are certainly more convenient and

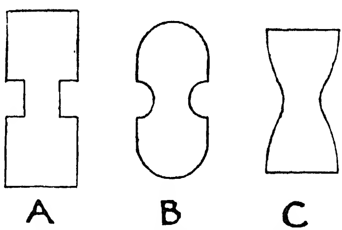

Fig. 1.—Shapes of Cement Briquettes.

can be tested with less powerful machines. Some persons even advocate the use of briquettes only $\frac{1}{2}$ in. square, but briquettes so small are not to be recommended, as the results will be less constant than with larger ones.

Preparing Briquettes.—The operation of making briquettes must be attended with care. The temperature of the cement, water of mixture, air, and of the water in which the briquettes are placed after having set, should be maintained uniformly at 60° Fahr., as variation of temperature is injurious to the hardening. The requisite quantity of water (neither more nor less) should be added to the cement, and the whole thoroughly mixed together either by means of a trowel or, better, by a small gauging-machine. The paste must then be filled into the metal moulds, pressed so as to exclude all air-bubbles, and

smoothed on the top with a trowel. The moulds containing the cement must be placed where they will not be disturbed, so that the cement can have full opportunity of setting properly; they may with advantage be covered with moist blotting paper to prevent too rapid evaporation of the water of mixture. At the end of 24 hours, the briquettes must be released from the moulds, and placed in water, where they must remain until they are taken out to be tested.

WATER.—The quantity of water used in making briquettes has a great influence on the results of the tests. Too much water is injurious, and no more, therefore, ought to be used than is necessary to bind the cement. This may vary from 18 to 25 per cent. of the weight of the cement, the finest and quickest-setting requiring most water. Fresh cement takes more than stale cement, on account of the free lime in it which requires slaking. The exact amount must be left to the judgment of the person making the test, but it may be interesting to give the quantity of water used in Germany for different mixtures of cement and sand, the proportions being all obtained by weight:—

TABLE IX.—QUANTITY OF WATER REQUIRED IN BRIQUETTES.

	Cement.	Sand.	Water.
Neat cement	100	—	27·5* 25†
1 cement to 1 sand	50	50	12
1 „ „ 3 „	25	75	10
1 „ „ 4 „	20	80	10
1 „ „ 5 „	16·6	83·3	10

Need we add that the water used with the cement ought to be pure, free from earthy and organic matter, &c.

TESTING MACHINES.—Several kinds of testing-machines are in use, among which we may mention those of Adie,

* Quick-setting. † Slow-setting.

Bailey, Michele, Frühling and Michaëlis, Quillot, Studt, and Faija. They do not all give the same results, as they vary in steadiness and accuracy of workmanship, but a detailed description of each would be out of place here. They are nearly all adaptations of the lever, the stress in some being applied by means of a weight moving along a steelyard; in others by pouring sand, shot, or water into a can at the end of the lever.

Fig. 2 is a side elevation of Mr. Faija's machine, which is thus described in his valuable little book on "Portland

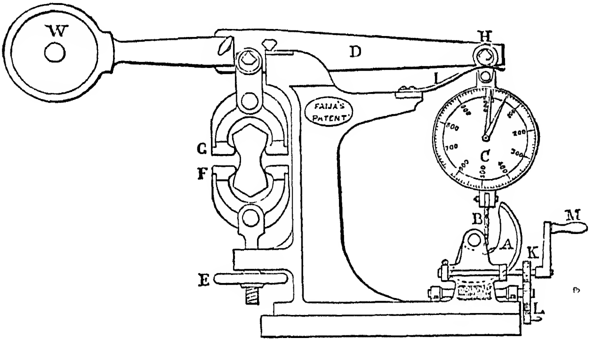

Fig. 2.—Faija's Cement-Testing Machine.

Cement for Users":—"The briquette to be tested is placed in the clips F, G, in which it is fixed by turning the wheel E attached to the lower clip F. The strain is applied by turning the handle M, which by means of gearing, depresses the end of the long arm of the lever, and the strain applied to the briquette is measured by the spring-balance C, through which the power depressing the long arm is passed. The pointer on the dial carries a loose finger, which stops at the position on the dial plate indicating the strain in pounds at which the briquette broke. The gearing is so arranged, that by turning the handle M, at an easy pace, the strain is applied to the briquette at the standard rate of 400lbs. per minute." The machine is made in two sizes,

the smaller capable of testing anything up to 1,000 lbs. and the larger anything up to 1 ton.

In ascertaining the strength of any cement, the average of not less than three tests ought to be taken.

Age of Briquettes.—The usual age at which neat cement briquettes are tested is seven days, and very often another set of three or more is broken at the age of fourteen, and a third at the age of twenty-eight days. In some cases, three-days' tests are taken, but tests at early dates are not always to be depended on, for it not unfrequently happens that one cement at the age of three days gives better results than another, while at later dates the advantage rests with the latter.

Three-days' tests ought not to be specified alone, but always in conjunction with tests at seven days, and the latter should shew an increase of strength over the former. What the amount of this increase will be, cannot be definitely stated. "A slow-setting cement," says Mr. Faija, "will probably increase 50 per cent. between the three and seven days' tests, and 25 per cent. between the seven and twenty-eight days, whereas a quick-setting cement may increase but little;" therefore, "the tensile strength of a quick-setting cement should be greater at the shorter dates than a slow-setting one."

A cement which developes great strength in a short time may possibly (but not by any means necessarily, of course,) prove to be a dangerous one, liable to "blow" and disintegrate some time afterwards, owing to the presence of lime in excess. Instances are recorded of cements which show great tensile strength at the end of one month, but which fall to pieces at the end of six months.

Tensile Strength required by various Engineers.—There are in England no standard rules for the guidance of persons using cement, as there are in Germany and Austria. Here every engineer specifies the strength, fineness, &c., of the cement to be what his own sweet will directs; and, consequently, the varieties of specifications prove quite bewildering to manufacturers. Mr. William Gostling, with a touch

of humour, drew attention to this matter by a communication printed in the *Proceedings of the Institution of Civil Engineers* (1879–80, part iv.). He gave three lists, which he had compiled, of specifications; twenty-one specifications showed thirteen different tests for fineness, ten for weight, and thirteen for tensile strength. The tensile strengths required by the specifications varied from 200 lbs. to 444 lbs. per sq. in. for neat cement broken seven days after gauging, and from 140 lbs. to 170 lbs. per sq. in. for briquettes made of cement and sand (1 to 3), broken at the age of twenty-eight days.

Mr. Grant, in the original specification of cement for the Metropolitan Main Drainage Works, required a tensile strength of 177·8 lbs. per sq. in., but afterwards increased it to 350 lbs. Still more recently (namely, in 1880), he again raised the test, and required neat cement to bear at least 400 lbs. per sq. in. after seven days, and 550 or 600 lbs. after twenty-eight days, the briquettes in all cases being one day in air and the remainder in water. Mr. V. de Michele in 1880 considered a strength of 300 lbs. per sq. in. at seven days sufficient, while Mr. Faija follows Mr. Grant's middle test for the seven-days' strength, but specifies his requirements for tests at the ages of three days and twenty-eight days, namely, 250 lbs. at three days, 350 lbs. at seven days, and 450 lbs. at twenty-eight days. Mr. A. E. Carey requires 180 lbs. at three days, 350 at seven days, and 550 at twenty-eight days for neat cement; and 120 lbs. at seven days, and 200 at twenty-eight days, for briquettes of cement and normal quartz sand (1 to 3). Some manufacturers guarantee a strength of 444 lbs. per sq. in. at the age of seven days; Mr. G. F. White has stated that the average tensile strength of the cement made by his firm during a period of two years ranged from 502 lbs. to 524 lbs. per sq. in. Cements have been tested which give a tensile strength of more than 700 lbs. at seven days, but such cements show little increase in strength afterwards, and as they most likely contain too much lime, are probably somewhat dangerous. In modern specifica-

tions the tensile strength of neat cement ranges from 450 to 550 lbs. per square inch at seven days, and from 700 to 850 lbs. at twenty-eight days.

Tensile Strength of Cement and Sand.—Although the testing of cement neat is undoubtedly important, it does not really give an exact idea of the working value of the cement; for cement is scarcely ever used neat, but almost invariably in combination with sand and other substances. This is one strong argument in favour of testing mixtures of cement and sand, so that the test may bear a closer relation to the uses to which the cement must be put in actual construction. Another argument, even more forcible, is that the strength of neat cement does not bear a fixed ratio to the strength of the cement when mixed with sand, and many figures might be quoted to show that, of two cements, one gives better results when tested neat, while the other is the stronger when tested with sand.

The German and Austrian standard rules prescribe such a sand-test; they require the briquettes to be composed of one part cement and three parts dry sand (by weight), to remain in air for one day after gauging, and then to be placed in water for a period of twenty-seven days; at the end of this period they are to be tested. The German rules in 1878 required the tensile strength of such briquettes to be 10 kilogrammes per square centimètre (142·22 lbs. per sq. in.); while the Austrian rules demanded 12 kilos. for the same area (170·7 lbs. per sq. in.). In 1887 the German standard was raised to 16 kilos. per square centimètre, or 227·5 lbs. per sq. in. Thirty-three briquettes made from Messrs. G. & T. Earle's Portland cement and three parts sand, in accordance with the German rules, were tested by Mr. Faija in 1886, and gave an average strength of 251 lbs. per sq. in. at twenty-eight days. Dr. Michaëlis mentions one cement which, tested with three parts sand, broke with 457 lbs. per sq. in. at twenty-eight days.

There are two common objections raised against the sand-test; first, the great delay which a test extending

over twenty-eight days involves (and briquettes containing sand, it must be remembered, cannot be fairly tested at an earlier date); and second, the difficulty, nay, almost the impossibility, of obtaining natural sand of such a uniform physical and chemical composition as will give always identical results.

In Germany, a standard sand can be obtained from the Government testing-establishment at Berlin; this sand has all passed a sieve with 387 meshes per sq. in., and has all been retained on one with 774. The second objection, therefore, loses in that country a great part of its force. In England no such standard sand exists, but any kind is called "normal" or "standard," if it has all passed a No. 20 sieve and been retained by a No. 30. An attempt, however, is being made to render a special kind of sand, obtained at Leighton Buzzard, the standard sand for this country.

Mr. Grant, however, the great advocate of testing cement with sand, declared in 1880 that he had "recently met with two sands which, though both clean, sifted through the same sieves, and not much unlike each other even under the microscope, gave results that differed by 50 per cent." "From this," he continued, "it was clearly as important to test the quality of the sand or gravel used with cement as it was to test the cement itself."* This would be multiplying the difficulties of testing, and therefore we think Mr. Faija's suggestion, made after the reading of Mr. Grant's paper, a good one, namely, that cement should be tested neat, and that for the sand-test the sand used should be of the kind which would be used in the actual works for which the cement was required. This would give the architect or engineer a knowledge of the strength to which the particular structure about to be erected might be expected to attain. Table I., page 20, contains the results of tests made by Mr. Grant on the strength of neat cement, and of cement and sand in different proportions, and the results of other experiments will be found in Chapter X., and in Figure 3, page 74.

* *Proceedings of the Inst. C. E.,* 1879–80, part iv.

COMPRESSIVE STRENGTH.—Testing by compression is seldom or never specified, but the results of such tests, especially with briquettes of cement and sand, are of interest, as this test approximates more closely to the actual stress which the cement has to bear in certain parts of a building (foundations and arches, for instance), than does the test by tension. The shape of the briquettes largely influences the results, as it does in the case of tensile tests. The resistance of cubes, columns, cylinders, &c., as can easily be understood, varies considerably. For comparison, cubes of a certain size are most convenient.

The resistance which Portland cement offers to compression bears an approximate relation to that which it offers to tension, although the relation is not as uniform as in cast-iron and wrought-iron. Messrs. Dyckerhoff found that cements, tested under the same conditions as to area, &c., and with three parts of sand to one of cement, exhibited a resistance to compression twenty times as great as that they offered to tension, but this apparently is an abnormal ratio. Professor Bauschinger states that with nine cements the ratio between compressive and tensile strengths varied from 7 to 1 to 11 to 1. On the Continent it is usually considered that the resistance of a cement-mortar (1 to 3) to compression should be ten times as great as its resistance to tension. Mr. Faija found that four cements gave results in which the ratio varied from about 7 to 1 to 9 to 1; at the age of 28 days, the resistance to crushing varied from 4,270 lbs. to 4,780 lbs. per sq. in., and the resistance to tension from 480 lbs. to 696 lbs. These figures are the average of three tests in each instance; the briquettes crushed were only 1-in. cubes. See also Table IV., page 30.

Considerable objection has been taken to the compression-test, because the slightest inequality of the surfaces of the briquette may cause fracture under a comparatively small stress. This is perfectly true when the briquettes are very small, but the difficulty is not insurmountable. If, instead of 1-in. cubes, 6-in. cubes were made, and brought to a

smooth surface on two opposite sides with plaster of Paris or neat cement, or in other suitable manner, and crushed, as in the case of building-stones, more accurate and uniform results of considerable value would be obtained.

When the resistance of building-stones to crushing began to be tested, small cubes measuring 1 in. or $1\frac{1}{2}$ in. or 2 in. each way were used, but the results varied to such an extent, on account of the irregularity, &c., of the specimens, that it was found necessary to test larger pieces. This was rendered possible by Kirkaldy's powerful machines. The larger pieces invariably gave higher results per square inch than the smaller; thus, nine experiments on 2-in. cubes of Yorkshire stone gave a mean resistance of 4·38 tons per square inch, while 6-in. cubes gave a mean of 4·91 tons; and 2-in. cubes of Bath stone (Box) crushed with ·66 ton per square inch, while 6-in. cubes required 1·5 tons per square inch to crush them. Mr. Faija's tests of 1-in. cubes of neat cement showed compressive strengths varying from 1·91 tons to 2·13 tons per sq. in. at the age of twenty-eight days, and increasing to three or four tons at the end of six months. Some tests by Mr. A. E. Carey showed the compressive strength of a neat cement to be at three months 7,392 lbs. per sq. in., or 3·3 tons. Tests of larger concrete cubes will be given hereafter. (See Tables XVI., page 127, and XXI., page 183.)

TABLE X.—TENSILE AND COMPRESSIVE STRENGTH OF PORTLAND CEMENT, in lbs. per sq. in.

Composition (by weight).			Tensile strength.					Compressive strength.				
Cement.	Lime in Dry State.	Sand.	Three of Sand.	Five of Sand.	Six of Sand.	Seven of Sand.	Eight of Sand.	Three of Sand.	Five of Sand.	Six of Sand.	Seven of Sand.	Eight of Sand.
1	...	3, 5, 6	224·8	138	91	...	...	4,822	2,341	1,549	...	...
1	$\frac{1}{8}$	3, 5,	236·2	159·4	..	...	...	5,509	3,036	...	...	...
1	$\frac{1}{4}$	3. 5, 6	258·9	150·8	145·1	...	..	6,292	3,193	2,504	...	...
1	$\frac{3}{8}$	5, 6, 7	...	139·4	132·3	119·5	...	...	3,618	2,481	2,066	...
1	$\frac{1}{2}$	5,6,7,8	...	128	133·7	99·6	86·8	...	3,412	2,716	1,941	1,643
1	$\frac{3}{4}$	6, 7, 8	...	...	115·2	91·1	74	...	..	3,521	2,535	1,847
1	1	8	...	...	...	...	76·8	...	...	...	...	1,871

The preceding table is based on results obtained by Messrs. Dyckerhoff, and shows the relation between the tensile and compressive strengths of cement mortar containing sand and lime in varying proportions; the sand had all passed a sieve with 387 meshes to the sq. in., and had all been retained on one with 774 meshes; the cement took four-and-a-half hours to set.

These tests were all made on briquettes twenty-eight days old, the first four series having been kept in air one day and in water twenty-seven days, the last three series having been in air the whole time. The briquettes were only small, those subjected to tensile stress weighing about ·33 lbs. each, and the others about ·43 lbs. each.

TRANSVERSE STRENGTH.—Mr. D. A. Stevenson specifies the following test of cement for small works, where a testing-machine cannot reasonably be required:—"The cement is to be made into blocks, 1 in. square and 8 in. long; these are to be immersed in water for seven days, and then tested by being placed on two supports 6 in. apart, when they must stand the transverse strain produced by a weight of 75 lbs. placed in the centre."*

Mr. Deacon, Water Engineer of Liverpool, contrived a simple apparatus for ascertaining the transverse strength of cement bars, by which no stress is put upon the bar by the weights until a lever is moved. He recommends that three bars of neat cement, 10 in. by $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in., be made, kept in water for seven days, and then broken on supports $9\frac{1}{2}$ in. apart; if not more than one of the three break with a weight of 150 lbs., the cement may be considered satisfactory.

For use in the formula $C = \frac{3LW}{2BD^2}$ (see Chapter XVI.), Mr. Stevenson's test assumes the value of C to be 675, and Mr. Deacon's assumes it to be 633; these constants will give the breaking-weight (W) in lbs. Calculations will be much simplified if C be taken to equal six, the breaking-

* *Proceedings Inst. C. E.*, vol. lxxxvii. part i.

weight being then in cwts.; this will be near enough for all practical purposes, for a large factor of safety must always be used in calculating the safe load for concrete structures.

The following table has been compiled from figures given by Gillmore in his book on limes, &c. The bars were made in 1860, kept in water, and broken by a force applied at the middle, the ends being simply supported:—

TABLE XI.—TRANSVERSE STRENGTH OF PORTLAND CEMENT.*

No.	Proportion by volume.	Size of bars.	Clear span.	Age in days.	Average breaking weight in lbs.	Value of C., to give result in cwts.	Remarks.
		in.in.	in.				
1	English Portland cement .	2 × 2	4	320	1,536	10·3	Set under pressure of 32 lbs. per sq. in.
2	1 „ to 1 sand	„	„	„	1,263	8·4	
3	1 „ „ 2 „	„	„	„	950	6·3	
4	English Portland cement .	1 × 1	3	270	306	12·3	Not set under pressure.
5	1 „ to 1 sand	„	„	„	313	12·5	
6	1 „ „ 2 „	„	„	„	204	8·2	
7	1 „ „ 3 „	„	„	„	91	3·6	
8	1 „ „ 4 „	„	„	„	74	2·9	
9	1 „ „ 5 „	„	„	„	45	1·8	
10	1 Roman cement to 1 sand	2 × 2	4	100	585	3·9	Set under pressure of 32 lbs. per sq. in.

It will be noticed that the value of C deduced from these experiments is considerably more than is required by the tests of Mr. Stevenson and Mr. Deacon, but it must be remembered that the latter are for tests at seven days, whereas Gillmore's experiments were on bars 270 and 320 days old. The abnormal strength of No. 5, seems to point to some error or irregularity in the testing, either of it or of some of the others in that series.

ADHESIVE STRENGTH.—Cements have not been as frequently tested for adhesion as for tensile strength. A

* For the transverse strength of concrete beams, see Table XXII., pages 190-1.

somewhat elaborate series of experiments with American cements and bricks is tabulated in Gillmore's "Limes, Hydraulic Cements, and Mortars," and General Sir C. W. Pasley in England, about fifty years ago, made similar experiments by tearing apart bricks and various building-stones which had been united by an artificial cement. As far as the adhesive strength of cement is concerned, these latter experiments are quite out of date. A circular issued some years ago by the Selenitic Cement Company shows that a force of 23 lbs. per sq. in. is required to tear apart common stock-bricks after they have been united for twenty-eight days by a mortar consisting of one part Portland cement and four parts sand. Mr. Grant found that bricks cemented together with mortar composed of one part cement and two parts sand required, at the end of twenty-eight days, a force varying from 15 lbs. to 30 lbs. per sq. in. to tear them apart.

The most extensive series of experiments on the adhesive strength of Portland cement was carried out by Mr. Mann. The tests were made by tearing apart small pieces of sawn, close-grained limestone, which had been joined together with cement. His experiments showed that the adhesive strength did not bear a uniform relation to the tensile or cohesive strength, but varied from about 1 to 5 to 1 to 9 in the seven days' tests, and from 1 to 3 to 1 to 5 in the twenty-eight days' tests. The adhesive strength, it will be seen, increased more rapidly than the cohesive, in the twenty-one days which elapsed between the two tests. He also proved that the finer a cement is ground the greater is its adhesive strength. The average adhesive strength of neat Portland cement, as tested by Mr. Mann, may be considered to be between 80 lbs. and 90 lbs. per sq. in., at twenty-eight days; the tests being carried out with cement bedded between pieces of sawn, close-grained limestone.

The adhesion varies not only with the quality of the cement, but also with the quality as well as quantity of the sand, the porosity of the substances joined together, their degree of saturation, and, of course, the length of

time during which they have been joined. The thorough saturation with water of the materials to be united, and

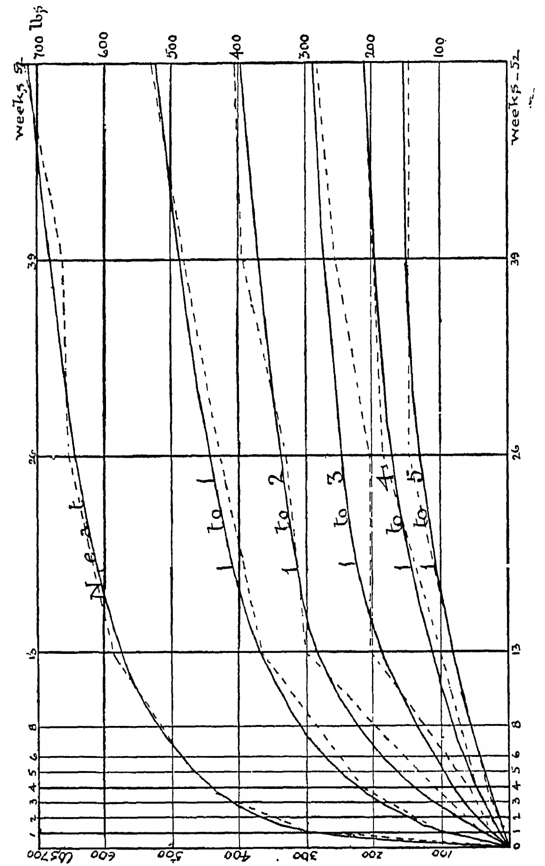

Fig. 3.—Diagram showing the effect of age on the increase of strength of Portland cement mortars.

the fineness of the cement, are important if high results are to be obtained.

Increase of Strength.—The accompanying diagram (Fig. 3) shows graphically the tensile strength, to the age

of one year, of Portland cement mixed with different proportions of clean pit-sand. The dotted line represents the actual breaking strength at the various dates, and the full line shows the probable mean curve of strength. The figure is based on experiments made by Mr. Grant, in 1862–3,* on briquettes of the shape marked A in Fig. 1. As we have stated, such briquettes give considerably lower results than the briquettes of better shape which are now used. For this reason, 50 per cent. has, in each case, been added to the strengths obtained by Mr. Grant.

The chief lesson to be learnt from Mr. Grant's tests is the difference in the rate of hardening of different mortars; for instance, neat cement would support 300 lbs. at one week; 1 to 1 mortar would do the same at 7 weeks; 1 to 2 at 15 weeks; and 1 to 3 not until after a year. When we are told that the supports of ordinary concrete floors may be struck in one week after the floors have been laid, we have only to refer to this figure to be convinced of the danger of following such advice. A period of from four to six weeks ought always to elapse before any stress is put on such floors, either by removing the supports or by traffic.

It must not be considered that all cements increase in strength in the degree shown in the figure, or that the ratio beween the neat cement and the mortars is always the same; the figure must be taken as approximate only. The tensile strength of the neat cement at seven days is only 300 lbs. per sq. in., even after allowance has been made for the imperfect form of the briquette used in testing; nowadays, a strength of 450 lbs. to 600 lbs. is common. The strength, at different ages, of mortars made from cements of various initial strengths, may be *roughly* estimated by using a different scale for measuring the curve of strength from the base line; thus Scale 1 (see Fig. 3) may be used for cements with a strength of 350 lbs. at seven days, and Scale 2 for 400.

Professor Unwin states that "for ordinary tension

* *Proceedings Inst. of C. E.*, vol. xxv. (1865–6).

briquettes the gain of strength is nearly proportional to the cube root of the time of hardening, and that both for a neat cement and cement mortar." In other words, if the strength at seven days be taken as 1, the strength at twenty-eight days will be 1·6, and at six weeks 2.

Durability.—The further question remains—Is the strength of Portland cement permanent? Mr. Grant says that the process of hardening goes on for years, and "there is no reason to fear that good cement ever deteriorates." His opinion is based on the result of a series of experiments extending over ten years (1858 to 1868); the tests during the last three years gave slightly lower results, but this he considers to have been due to the fact that the briquettes had been neglected and moved from place to place owing to the death of the person who had had charge of them. We need not say that Mr. Grant's opinion on any matter concerning Portland cement carries great weight.

Mr. A. E. Carey, in a paper read in November, 1891, before the *Institution of Civil Engineers*, said:—"The molecular structure of Portland cement changes with age, its hardness and brittleness increasing, and its elasticity diminishing. There is a point, therefore, at which the cement begins to show a falling off in tensile strength, while the compression tests continue to improve. The gauging of cement with sea-water [instead of fresh] allows this result to be attained more speedily with the same cement."

Experiments recently made by Baron Quinette at Havre, show a great falling-off in the tensile strength of neat cement after the first year, while that of *mortars* goes on increasing "during several years."

CHAPTER VII.

MATRICES—(*continued*).

III. Artificial Cements (*continued*) :—3. Portland cement (*concluded*)—Resistance to fire—Soundness—Time of setting—Air-slaking—Storing—Expansion and contraction—Specifications.

Resistance to Fire.—The superiority of Portland over some other cements and plasters in respect of resistance of fire, has already been mentioned in Chapter III., pp. 34-39. It is, of course, acknowledged that Portland cement is not proof against great heat and sudden quenching, but it may be asked—What material is? Certainly iron and steel are not; limestone, granite, and sandstone are not. Indeed, very few of the materials which are used in modern buildings can withstand such a test. Portland cement is undoubtedly a *fire-resisting* material, and a good one, but it is not,—and very few materials are,—*fire-proof.* Mr. Thaddeus Hyatt, in his book on "Portland-Cement-Concrete," mentions a "New Portland Cement, specially prepared to resist fire," but apparently this is not in the market to-day.

Soundness.—The fineness, tensile strength, and soundness are three of the most important particulars to be ascertained respecting any Portland cement. The fineness of a cement is an indication, other things being equal, of its sand-carrying properties,—the finer the cement the more sand will it take. A finely-ground cement is also less likely to be unsound than a coarse cement. The importance of a high tensile strength is patent to every one. But if a cement be finely-ground and of great strength, and withal have not soundness, it ought not to be used.

An unsound cement may attain great strength at first; concrete made with it may harden properly, and seem for weeks, and even months, to be thoroughly hard and sound, but gradually a change is apparent, the concrete begins to disintegrate, and after a time becomes an almost incoherent mass of rubbish. Then, the architect must perforce order the work to be done over again, and time and money are lost. But sometimes the defect is not observed before the final certificate is granted; perhaps the foundations are covered before the unsoundness is apparent, or the floors have their upper and lower surfaces finished, and so on, but sooner or later the failure is visible. In one case, 18 in. brick walls were thrust out of perpendicular by the expansion of concrete floors made with unsound cement.

A test for soundness can be carried out without much difficulty, but as some cements take such a long time before their unsoundness develops to any dangerous extent, an artificial means of accelerating the hardening process has been desired. Some persons have advocated, but not wisely, the making of thin pats of cement-paste on an iron plate and heating them on a gas-jet or in front of a fire. The best apparatus which has yet been devised is that described by Mr. Faija in his book on Portland cement.

The fact that moist heat accelerates the hardening of cement is the leading idea in Mr. Faija's test, and this is turned to account by placing the cement pats on a slip of glass within a closed vessel, containing water under the glass; this water is kept at a fairly uniform temperature of about 112 deg. to 117 deg. Fahr. After remaining three hours in the damp atmosphere of this vessel the pats are put into the hot water and allowed to remain there for twelve or fifteen hours, when they are taken out and examined for cracks, lifting from the glass, warping, &c. If these are visible, the cement must be accepted with caution, or, in bad cases, condemned altogether.

It is, however, possible for anyone to carry out a test which will be of some aid in ascertaining the soundness of a cement, although it is not of equal value to the test

already described. Take samples of the cement from three or four bags or barrels, immediately on their arrival at the building-site, and mix the different samples together dry. Then make, on two pieces of glass, two pats of neat cement, say, 2 in. or 3 in. diameter, and about $\frac{1}{4}$ in. thick at the centre, but thin at the edges. The time of setting may be ascertained during the progress of this test.

When the pats are set hard, place one in water and examine it daily. If the cement have any tendency to "blow,"—*i.e.*, if it be unsound,—very fine cracks will appear at the edges, and the edges may leave the glass. The other pat, kept in air, ought when hard to have a greyish-white hue; a buff colour indicates an "over-clayed" cement, and such cements are weaker than cements of proper composition, and are, as has already been stated, liable to crumble away on exposure to the atmosphere.

Another cause of disintegration is the presence of free quicklime in the cement; the danger arising from this can be minimised by properly air-slaking the cement before using it, but an over-clayed cement cannot be improved,—it ought to be rejected. Similar pats made of cement and sand (1 to 3) may be made and tested as above with advantage.

TIME OF SETTING.—The time of setting of different Portland cements varies from a few minutes (say, ten) to as many hours. If a pat of neat cement is indented by a moderate pressure of the thumb-nail at the end of two hours, it may be considered slow-setting. It is customary now to notice the time of "initial set," that is, the commencement of the stiffening process, and the "set hard," which is the time when the cement will bear without indentation a moderate pressure of the thumb-nail. The former is valuable, as it enables us to form an idea of the limit of time within which the cement ought to be deposited in work after being gauged. It is determined by gauging a sample of cement and observing one or more pats kept in air. If greater accuracy be required, the time of setting can be ascertained by the needle test, but the thumb-nail test is really quite sufficient.

As a rule, a highly-burnt cement sets more slowly than one lightly burnt, but there are exceptions, and more frequently the rate of setting depends rather on the composition of the cement than on the burning. An excess of alumina increases the rapidity of the setting, as in Roman and similar cements; excess of lime has the opposite effect. Fineness of grinding also hastens the setting, and to counteract this effect many manufacturers add from 1 to 2 per cent. of gypsum during the grinding process; larger quantities of this material endanger the permanence of the strength of the cement.

The time of setting is delayed by storing and thoroughly air-slaking the cement, and the same effect can be produced by adding sulphuric acid or gypsum (sulphate of lime) on gauging. In either case, the maximum strength of the cement is more rapidly attained.

Experiments made by Mr. Grant in 1877 showed that cement spread in air for seventeen hours took five or ten minutes longer to set, and bore at seven days 5 per cent. more tensile stress than the same cement gauged as soon as it was taken from the sacks. Experiments by Messrs. Dyckerhoff confirm this, and show further that the addition of 1 per cent. of gypsum to a cement, which set in twenty minutes, delayed the setting to 600 minutes, and 2 per cent. delayed it to 840 minutes, and in both cases the strength of the cement, whether tested neat or with sand, was considerably increased; the increase of strength with 2 per cent. of gypsum was about 13 per cent. at the end of a year.

Storing the cement for some months altered the time of setting from twenty minutes to 630, and the stored cement mixed with three parts standard sand was 20 per cent. stronger at the end of a year than the original cement tested in the same way.

The advantages possessed by slow-setting cements in strength, convenience of manipulation, &c., are of great value, and such cements are for ordinary purposes preferable to quick-setting ones.

AIR-SLAKING.—"Air-slaking" is the name given to the

process of converting the quicklime, present in cement, into hydrate of lime, by means of the atmosphere. It depends for its action on the fact that quicklime has so great an affinity for water that it absorbs it greedily from ordinary air, and is converted into slaked lime by an amount of moisture so small as not to cause the cement itself to set. Air-slaking is effected by storing the cement in bulk, so that the air can have free access to it.

Some persons consider that ordinary Portland cement does not contain more than 1 per cent. of free lime, but as no method of accurately ascertaining this exists, the figure is, perhaps, more or less guess-work. Judging from the increase of bulk, which ensues from thorough air-slaking, we are inclined to believe that cement of that description contains in many cases 3 or 4 per cent. of free lime, and some cements probably contain considerably more than this. When we remember that calcium oxide is converted by slaking into calcium hydrate, a substance two or three times its bulk, we cannot fail to see that the development of this slaking action in a cement-paste which has already begun to set, must be injurious and must at the very least lessen its ultimate strength, while in extreme cases it may prove disastrous.

The effects of properly air-slaking Portland cement are (1) retardation of the time of setting,* (2) increase of strength, (3) lessening or the total loss of any tendency to "blow," (4) diminution of expansion in setting, and (5) increase of bulk and consequent decrease of weight per bushel.

STORING.—A clause is frequently inserted in specifications to the effect that the cement must be stored in bulk for a certain length of time in a suitable room. Some cements naturally require longer time for "purging" or air-slaking than others, as they contain more quicklime; and some cements are purged to a considerable extent by the manu-

* Occasionally a cement which is slow-setting when freshly ground becomes quick setting after storage, but in such cases it will generally be found that the cement contains gypsum, which has been added to retard the setting.

facturers before they are put into bags or barrels, and consequently may require little or no purging after their arrival at the works.

As we have already explained, Portland cement ought not to be used quite fresh, but opinions differ as to the length of time which it ought to be kept before being used. An extremely fine cement theoretically requires no exposure at all. A good cement should be sufficiently air-slaked by an exposure of from one to three weeks. It is not enough to keep the cement in bags or barrels for that length of time, but it must be emptied upon a wooden or damp-proof concrete floor in a dry building, to a depth of 2 ft. or 3 ft., and allowed to remain there for the specified time, being occasionally turned over. Even cement, which has been kept in bags for months, ought to be stored in bulk before being used.

Great care must be exercised that the cement is not stored in a damp place, such as a cellar, or on a floor of flags or other material, between the joints of which, or through which, moisture can easily rise, as this moisture attacks the cement and causes it to set into hard "cakes," which are almost as worthless as so many lumps of limestone. Cement, exported to a warm and moist country, has become lumpy, even though it has been carefully packed and kept in paper-lined barrels, and concrete made from it has proved a failure. Exposure to heat is also detrimental to cement.

There is a limit beyond which cement ought not to be kept, but it is impossible to lay down any hard-and-fast rule, as the limit will vary according to the nature of the cement and the manner of storage. The coarser the cement the longer the exposure which is required.

Where a test for soundness is specified, there is not so much necessity for specifying that the cement shall be stored in bulk for a definite period; because, if the cement be unsound when fresh, it of course falls short of the specification, and can, therefore, be rejected. The contractor will in this case be only too glad to render it sound, if that can be done by storing it in bulk for a few weeks.

Where, however, no test for soundness is specified, the proper storage of the cement in bulk (not in bags or barrels) for some weeks, must be required. The contractor may try to evade this demand, but it must be insisted on, even when the cement has been obtained from a manufacturer of good reputation, whose name may have been mentioned in the specification. Otherwise the best results will not be obtained.

Expansion and Contraction.—With respect to the expansion and contraction of cement during hardening, Mr. Grant, in his paper in 1880, gave the inferences which he had drawn from the experiments of Messrs. Dyckerhoff and others. They were:—"1. That all cements expand more or less when hardening in water; 2. That the expansion of good cement is so very slight that in practice it need hardly be taken into consideration; 3. That it is greatest when the increase of strength is most active; 4. That it diminishes in proportion to the addition of sand; 5. That it is greatest with new cement, and least with that which has been kept in stock; 6. That it is increased by the addition of gypsum; 7. Further experiments prove that it is greatest with over-limed or lightly-burnt cements, and that all cements contract when drying, and expand on being put into water."

The experiments by Messrs. Dyckerhoff, to which Mr. Grant referred, were made on twelve varieties of cement, at the ages of 1, 4, 13, 26, 39, and 52 weeks; prisms 10 centimetres long (= 3·97 ins.) and 5 centimetres square were placed in water, and their expansion was noted in millimetres. The results showed that a bar of good air-slaked cement and sand (1 to 3) had expanded only $\frac{7}{20000}$ of its length in a year; in other words, a bar 1000 ins. long (83·3 ft.) would be only ·35 of an inch longer at the end of a year. The addition of 2 per cent. of gypsum seemed to double the amount of expansion, while the addition of 5 per cent. increased it about twelve-fold.

No harm can be done by the moderate amount of expansion which ordinary cement concrete undergoes in the pro-

cess of hardening, as in practice the force of expansion will be resisted by the dead weight of walls or ground or other material against which the concrete abuts, and the result will be the compression, to a slight extent, of the concrete.

This expansion during hardening must not be confounded with the expansion and contraction due to changes of temperature. The cracks, which occur in badly-laid paving, and, sometimes, in walls of great length, are most frequently due to the effects of heat and cold, and can be prevented by a little forethought. All materials are subject to variation under changes of temperature, and it is the duty of the architect and engineer to take note of such variation, and to counteract its ill effects. Special joints are required to allow for the expansion and contraction of large iron roofs and bridges, and it is no reason for decrying concrete if somewhat similar precautions have to be adopted to keep it free from defects.

The actual amount of the expansion and contraction of concrete, caused by changes of temperature, has not often been tested. Mr. Thaddeus Hyatt found that neat Portland cement had "a lineal expansion of ·00137 for 180 degrees of heat as compared with ·0014 for wrought iron, a result so near that the expansion may be considered to be the same."*

Specifications.—The variety of specifications for Portland cement is somewhat bewildering. We have already mentioned Mr. Gostling's list of twenty-one specifications, almost all different, but Portland cement is now better understood, and specifications ought not to differ to the extent they did a dozen years ago. It is not possible, of course, to formulate a specification which shall be suitable for all circumstances; for instance, in the great majority of cases a slow-setting cement will be most useful, but there are cases where a quick-setting cement is quite necessary, such as foundations in running water, underpinning, &c. Some important characteristics of cement,—namely, its

* "Experiments with Portland Cement Concrete combined with Iron," p. 19.

fineness and soundness, need not vary, and the tensile strength need vary only for those works where quick-setting cement is required. Briquettes of neat quick-setting cement may be specified to give higher results at early dates (three and seven days) than those made from slow-setting, but lower results at later dates.

The German standard regulations, among other things, require that the cement shall be thoroughly sound,—that a thin pat of neat cement which, after setting on glass, is placed in water, shall not crack at the edges,—that not more than 10 per cent. of it shall remain on a sieve with 5,806 meshes to the square inch (the thickness of the wire being equal to half the width of the meshes), and that cements requiring more than half an hour to set, made into briquettes with three parts by weight of standard sand, and tested after being one day in air and twenty-seven days in water, shall have a tensile strength of 227·5 lbs. per square inch, and a compressive strength of 2,275 lbs. per square inch.

Mr. Grant in 1880 communicated to the *Institution of Civil Engineers* a specification based on the German standard regulations then in force. The chief requirements of this specification may be summarised thus:—*Fineness*, not more than [20 or 10] per cent. residue on a sieve of [6,400 or 5,806] meshes to the square inch; *tensile strength*, at twenty-eight days, of cement gauged with three times its weight of dry sand, which has passed a sieve of 400 and been retained upon one of 900 meshes to the square inch, to be [142 or higher number] lbs. per square inch for cement which sets when neat in less than two hours, and [170] lbs. per square inch for cement which takes from two to five hours to set neat.

If the weight and tensile strength of the neat cement be specified, Mr. Grant would insert the following clauses:—*Weight*, not less than 112 lbs. to the bushel; *tensile strength* of neat cement, at least 400 lbs. per square inch at the end of seven days, and 550 or 600 lbs. after twenty-eight days, the briquettes being one day in air and the rest in water.

Mr. Grant also required the contractor to store the cement in bulk in a suitable room until tests had been made.

Mr. V. de Michele considered that a simpler specification could be framed, which would answer the purpose quite as well as the one proposed by Mr. Grant. He suggested :— "1. The Portland cement, before being used, to stand 300 lbs. tensile strain per square inch seven days after gauging; the average of not less than three breakings being taken. 2. The cement to be finely ground, leaving a residue not exceeding 10 per cent. after passing a sieve of 2,500 holes per square inch. 3. Pat samples ½ in. thick, made at frequent intervals, and immersed in water within one hour, to show no cracks from expansion within forty-eight hours after gauging." "He would discard the weight per bushel test, as being useless and misleading."

Mr. Michele subsequently suggested another specification, which will be found in the *Builder* for April 2, 1892. We reprint it here, with a few verbal alterations, so that it can be more easily compared with his specification of 1880 :— "1. *Tensile strength,* 400 lbs. per square inch at seven days; the test bricks to be gauged by a skilled man, with any quantity of water, in any way he likes; the average of three to be taken, which shall represent about 100 tons or less:* the strain to be applied as quickly as possible. 2. *Fineness,* 10 per cent. residue on a 50 sieve (2,500 meshes to the square inch) made of wire one-hundredth of an inch in diameter; shaking to be continued until no more of the cement passes through the sieve. 3. *Soundness,* pats one-eighth of an inch thick, gauged on glass, immersed in water immediately, and left there for the whole period, must be absolutely sound at seven days; one pat to be made for each three bricks."

It will be noticed that the second specification demands one-third more strength than the first, and requires pats to be ⅛ in. thick instead of ½ in., to be immersed immediately, and to remain in water seven days instead of two; the

* Of cement.

latter specification is undoubtedly better than the earlier one, but is not as stringent as many recent specifications, of which the following summary of one submitted to the Society of Engineers will serve as an example :—

Fineness of Grinding.—The residue on a No. 50 standard sieve to be not more than ½ per cent. by weight, on a No. 76 sieve not more than 5 per cent., and on a No. 100 sieve not more than 12 per cent.

Time of Set.— A pat of neat cement gauged with the minimum of water at 60° Fahr. and placed on glass or other non-porous slab shall not commence to set in less than 8 minutes or take longer than 5 hours to set hard.

Soundness.—A pat submitted to moist heat and warm water in the Faija apparatus at 110° and 120° Fahr. respectively, shall show no cracks or signs of expansion after 24 hours.

Tensile Strength.—Briquettes of neat cement gauged with the minimum of water on a non-porous bed and placed in water 24 hours after gauging, shall carry an average tensile strain of not less than 350 lbs. per sq. in. at 3 days, 450 lbs. at 7 days, and 550 lbs. at 28 days.

CHAPTER VIII.

ANALYSES OF HYDRAULIC LIMES AND CEMENTS, AND THEORIES OF INDURATION (Table XII.).

ANALYSES OF LIMES AND CEMENTS.—It has been already stated that hydraulic limes (with the exception of magnesian limes) and cements (with the exception of plaster of Paris and allied cements), depend for their hydraulicity on the mixture of lime and clay from which they are produced, and that the proportion in which these ingredients exist, has a great influence on the value of the lime or cement. But the value does not depend entirely on the composition of the raw material, for hydraulic limes may be calcined from material containing from 8 to 20 or even 30 per cent. of clay, and Roman and similar cements from material containing 25 to even 40 per cent., while Portland cement, the most valuable of all, hovers in composition between the two, containing in the raw state from 23 to 28 per cent. of clay.

From this it is evident that, while clay possesses the power of rendering lime and cement "hydraulic," and while, roughly speaking, increasing quantities of clay confer increasing rapidity of set, yet other considerations, besides this of mere quantity, affect the real value of the product. Chief of these, are the degree and the duration of the heat, to which the raw materials are subjected in the kiln, and the presence of iron or other substances which act as "fluxes" and which, if present in excess, cause the fusion or vitrification of the material at a heat less than that required for the production of the best Portland cement clinker. Greater heat is required in the

TABLE XII.—ANALYSES OF HYDRAULIC LIMES AND CEMENTS.

Number.	Kinds of Limes and Cements.	Lime.	Silica.	Alumina.	Oxide of Iron.	Magnesia.	Sulphuric Acid.	Soda and Potash.	Undefined Ingredients, Loss, Water, &c.	Authority.
	HYDRAULIC LIMES.									
1	Aberthaw *Blue Lias*...	78·45	9·35	6·25	trace	...	...	...	5·70	H. Faija.
2	Barnstone ,, ,, ...	59·61	20·61	6·98	4·01	2·25	1·94	...	4·60	J. B. Dyer.
3	Warmsworth Cliff (Yorks) *Magnesian* .	58·4	0·5 *b*.	...	1·4	38·6	...	...	1·1	F. Hudson.
4	Teil (France) *c*.	61·83	14·78 *a* / 6·20 *b*	1·61	0·99	1·15	...	...	13·73	F. Bömches.
	NATURAL CEMENTS.									
5	Roman Cement	41·2	16·0 *a*.	22·2		1·7	...	...	18·9	Anonymous (*d*).
6	Medina Cement	49·8	19·0 *a*.	16·6		...	...	...	14·6	,,
	ARTIFICIAL CEMENTS.									
7	*Slag Cement*	46·53	24·10	16·30	0·93	2·08	2·05	...	8·01	G. R. Redgrave.
8	Portland Cement, *e*. ...	61·76	20·54	9·90	2·04	...	0·71	2·13	2·92	Henry Faija.
9	,, ,, ...	60·76	21·52	4·76	4·24	0·61	2·50	2·80	2·81	John Grant.
10	,, ,, ...	58·29	20·56	6·20	6·76	0·32	1·62	1·23	5·02	,,
11	,, ,, *f*. ...	58·20	17·10 *a* / 4·60 *b*	11·15	4·85	1·44	1·30	0·85	0·51	Henry Faija.
12	,, ,, ...	58·02	23·38	8·42	5·10	0·90	0·84	0·64	2·70	John Grant.
13	,, ,, ...	61·05	22·22	10·10	3·19	...	0·85	1·34	1·25	A. E. Carey.

a. Soluble. *b*. Insoluble. *c*. A well-known French lime, much used on the Continent for works in the sea, &c. *d*. Rivington's "Building Construction," Part III. *e*. Made on the Thames. *f*. Made at Stockton, near Rugby, by Messrs. Greaves, Bull & Lakin.

manufacture of Portland cement than of the others, and it is only by this means that the proper chemical changes, on which the peculiar value of the cement depends, can take place. If the calcination of Portland cement material were only carried to a certain point, a hydraulic lime would be the result. Roman and similar cement-stones fuse at temperatures below that required for Portland cement.

The preceding table gives analyses of various limes and cements, and it will be noticed that the Barnstone Blue Lias lime and the Portland cement No. 10, are very similar in composition. The small proportion of lime in the natural cements and the slag cement, may also be observed.

It does not appear to be very clearly understood what part each constituent plays in the setting of lime and cement. The lime and silica undoubtedly play the most important part, but the action of the rest is still somewhat obscure. Knapp, a German writer, considered that iron and alumina are only of indirect service, but that soda and potash, which combine with silicic acid to form silicates of soda and of potash, and are in that form soluble in water, act as "transferrers of silicic acid to the lime." Sulphuric acid, whether added in the form of acid or of gypsum (sulphate of lime), has the effect of retarding the setting, but in excess it is injurious; so injurious, indeed, is it considered in France, that any Portland cement which contains more than 1½ per cent. of it is condemned without further testing. Magnesia is another ingredient which has been loudly spoken against, its presence in Portland cement being said to result in the ultimate destruction of the latter if placed in the sea; the case against it has not been proved, and has probably been overstated.

Effects of Calcination.—The moisture contained in the raw materials is rapidly driven off in the kiln, and the carbonic acid gas forming part of the chalk or limestone is also quickly expelled; so far, the results of calcination are similar to those produced in the calcination of fat lime. But hydraulic limes and cements contain clay and other ingredients, and all, or, at any rate, most, of these are

affected by calcination. The reactions which take place are even now only imperfectly understood. It appears that the clay is split up into its component parts, namely, silica and alumina, at an early stage of the burning, and that the calcium oxide or quicklime, remaining after the expulsion of the carbonic acid gas, combines with these to form silicates and aluminates of lime, the exact nature and value of which depend upon the proportion which the several components of the raw material bear to one another, and upon the temperature at which they are burnt, and, further, upon the duration of the burning.

Theories of Induration.—One of the earliest theories of the setting and hardening of cement was that of Pettenkofer, published about 1850. He considered that calcination should, at a moderate temperature, convert the calcium carbonate into calcium oxide, and at a high temperature should effect "a chemical combination of silicic acid with alumina, iron, and the alkalies, the silica being by this means protected from at once combining with the lime, but made available for future chemical action under changed conditions brought about on the addition of water." When water is added, the silicic acid is freed from the combinations effected by calcination, and combines with the hydrate of lime (into which the water has converted the calcium oxide) to form silicate of lime; this "partially decomposes the other silicates of alumina and iron in the act of hydration, forming double hydrated silicates, which are practically insoluble."*

Knapp, another German writer, declared that a portion of the calcium oxide formed during calcination reacts upon the clay and converts it into a compound easily decomposed by acids. This compound and the excess of calcium oxide, when water is added, react upon each other in such a manner, he says, "that a solid stone-like silicate" is produced.*

* *Proceedings of the Inst. of C. E.*, 1879–80, vol. lxii., paper No. 1,649, by Messrs. Scott and Redgrave.

Another authority,—to wit, Mr. Guthrie, Demonstrator of Chemistry at the Sydney University,—states that at a comparatively low temperature the lime is converted into silicate of lime; and that a high temperature induces the formation, in addition to this, of aluminate of lime, and finally of a double silicate of alumina and lime. This double silicate, and also the aluminate of lime, on the addition of water form hydrated silicates and aluminates, which set by crystallising.

A French mining engineer, M. Le Chatelier, has published the conclusions at which he arrived after making numerous experiments with silica, alumina, and lime. A short account of these will be found in *The Engineer* for Sept. and Oct. 1888, and in *The Builder* for July 6, 1889. M. Le Chatelier discovered that the only combination of silica and lime, which will "set" on the addition of water, is the tri-calcium silicate, *i.e.*, $SiO_2 + 3CaO$; this, however, cannot be produced by simply burning these substances together, and it is therefore probable that its formation in cement-clinker is brought about by the influence of some other ingredients of the cement, perhaps iron and alumina or the alkalies. The following equation expresses the chemical changes, which take place on the addition of water to this tri-calcium silicate:—

$$\underset{\text{tri-calc. silicate}}{2\,(SiO_2,\ 3CaO)} + \underset{\text{water}}{9H_2O} =$$

$$\underset{\text{hydrated calcium silicate}}{2\,(SiO_2,\ CaO),\ 5H_2O} + \underset{\text{calcium hydrate.}}{4CaH_2O_2.}$$

The hydrated silicate of lime thus formed, is dissolved by the water, which becomes super-saturated, and consequently crystallisation suddenly occurs, the lime being deposited "in extremely attenuated fibre-like prisms, ... united by one extremity to a central point so as to form little spherical groups." Thus the changes are "the chemical one of hydration, and the physical ones of solution, super-saturation, and crystallisation."

With reference to alumina, M. Le Chatelier discovered

that several different combinations of this substance and lime "set like plaster when pulverised and mixed with water, but all decompose in excess of water, and when the excess is considerable, they may be completely dissolved." In the presence of free hydrate of lime, however, a hydrated aluminate of lime (Al_2O_3, $4CaO$, $12H_2O$) may be formed, which soon crystallises in a similar manner to the hydrated silicate of lime. An examination of the foregoing equation, representing the chemical changes which occur on the addition of water to the tri-calcium silicate, shows that four molecules of hydrate of lime are set free on the formation of the hydrated silicate of lime, and it is this hydrate of lime which, according to Le Chatelier, brings into action the tri-calcium aluminate in the cement. The result may be thus expressed:—

$$Al_2O_3, 3CaO + CaH_2O_2 + 11H_2O = Al_2O_3, 4CaO, 12H_2O.$$

Dr. Michaëlis recently declared that "highly silicious cements, poor in alumina, set slowly, sometimes too slowly; but from the moment of setting they harden with energy, continue to increase in strength for a long time, and finally attain the highest strength. Cements rich in alumina set quickly, sometimes too quickly,"* but can be made slower-setting by the addition of gypsum, the use of which, says the doctor, has been wrongly condemned.

It is probable that the action of slag cement may throw some light on that of Portland cement. Slag itself contains lime, silica, alumina, and other substances, in varying proportions. A slag suitable for conversion into cement may contain, say, 36 per cent. of lime, 30 per cent. of silica, and 23 per cent. of alumina. These have been converted, in the enormous heat of the blast-furnaces, into compound silicates of lime, alumina, &c., which undergo little or no change on the addition of water: they are practically inert. But when ordinary slaked lime in

* *Proceedings of the Inst. C. E.*, vol. cvii. (1891-2, part i.).

powder is mixed with the ground slag, a cement is formed which sets on the addition of water, and attains great strength. We know that slaked lime (calcium hydrate) does not set in water, and the ground slag itself has no hydraulic properties; it is evident therefore, that the setting must be due to a reaction between these substances. This seems to point to Knapp's theory as the correct one, but not conclusively, for, as Mr. G. R. Redgrave has stated, it is possible that the intense heat of the blast-furnace may result in the formation of compounds quite different in their action from those formed in the lower temperature of a Portland cement kiln.

Experiments by M. Perrodil, published in the *Annales des Ponts et Chaussées*, 1884, seem to show that Portland cement which is allowed to harden in the air, absorbs carbonic acid gas from the atmosphere to the extent of about 6 per cent. in the first six months, while cement immersed in water remains free from it. The briquettes, kept in water, and therefore free from carbonic acid gas, offered about twice as much resistance to compression as the others, between the ages of one and six months; but this, we may say, is an abnormal difference.

Many modern cements contain a greater proportion of lime than those described in Table XII.,—that is to say, from 62 to nearly 63 per cent.,—while the soluble silica is about 21·5 per cent., and the alumina and oxide of iron together from 10·7 to 11 per cent.

CHAPTER IX.

WATER.

Action—Insufficiency and excess—Quantity required—Effect of quantity on (1) the density of concrete, and (2) the strength of concrete—Loss by absorption, &c.—Concrete deposited in water—Impurity of water and its effects—Sea-water—Warm water.

Action.—Water is necessary for the setting and hardening of hydraulic limes and cements. It does not form a merely mechanical mixture with these in the way it does with pure hydrate of lime, but it unites chemically with them, as we have already seen, forming new compounds of an indurating nature.

Insufficiency and Excess.—It is evident, therefore, that the quantity of water added to cement or hydraulic lime is of no little importance. If too little be used, some of the lime and cement remains more or less in the form of powder and cannot attain to that strength for which it was intended; and the mortar or concrete is pervious to moisture, and therefore more liable to destruction by frost and atmospheric agencies. On the other hand, there is no doubt that an excess of water is injurious to the strength of the cement, whether neat or mixed with sand. The water is scattered in little globules throughout the paste and around these the cement sets; gradually the water evaporates, and on the briquette being broken, little globular cells, in which the water-drops had lain, are disclosed, and are seen at once to be a source of weakness. Excess of water also retards the hardening of the concrete, and there is the further danger that it may wash away some of the finest and best particles of the cement during the operation of mixing with sand and other material.

Quantity Required.—We have already seen (page 63), that from 18 to 25 per cent. (by weight) of water is used in making briquettes of neat Portland cement, while, for briquettes of cement and sand, the weight of water must be about 10 per cent. of the combined weight of the two dry ingredients. This 10 per cent. by weight is equivalent to about 12·5 per cent. by volume, or, in other words, one volume of water to eight volumes of cement and sand. But we must remember that this is for making briquettes in laboratories, where, it may be expected, no water will be allowed to run to waste or be lost by evaporation, and where none will be absorbed by any surfaces with which the briquettes come in contact. This is very different from the conditions which obtain in practice, where water may drain away from foundations into the ground, or drip through the centring of floors, or be evaporated by the heat of the sun, or dried by passing winds.

It is now generally conceded that it is better to use too much water than too little, but it is best, of course, to use the right quantity, neither more nor less. Mr. E. C. Clarke thinks that Portland cement concrete requires from 21 to 23 gallons per cubic yard. Mr. A. E. Carey said at the *Institution of Civil Engineers* (1891) that he had obtained the best results by using about 22 gallons of water per cubic yard of raw materials, or about 1 part by volume to 7½ or 8 parts, "less than this not securing that glassy film upon the surface of work which is so desirable, and, more than this, washing away some portion of the soluble alumina silicates [*sic*] which are the active ingredients in concretion." The quantity recommended by Mr. Clarke and Mr. Carey is practically identical with the quantity required in making briquettes, and leads us to imagine that they refer only to concrete deposited in wet or moist situations, such as works in the sea, or to concrete carefully protected after deposition.

Mr. H. K. Bamber says that good cement requires for its thorough induration 40 lbs. (*i.e.*, 4 gallons) of water per cubic foot. If we take the weight of such a cement at

112 lbs. per bushel, or 87 lbs. per cubic foot, it will be seen that he advocates the use of 46 per cent. (by weight) of water with cement. This is so much in excess of any other quantity which we have seen advocated for neat cement that we think he must refer to cement when used in concrete with materials which are of an absorbent nature.

Effect of Quantity on the Density of Concrete.—Some experiments made by Mr. Bamber in 1889 and 1890 are of considerable interest in this connexion.* He made six blocks of concrete, all consisting of one part new Portland cement, 2 parts sand, and 4 parts shingle. Two of these (A) were made with the "full quantity of water that the cement would take up," namely, 10 lbs.; two (B) were made with $7\frac{1}{2}$ lbs. of water; and two (C) with only 5 lbs. They were allowed to harden for two weeks before being disturbed. At the end of this period, one block of each kind was placed on a sea-wall, in such a position that they were covered and uncovered by the sea at every tide. After remaining there for a year, they were removed and broken through the middle. The block (A) was "very hard and perfectly sound and dry quite through to the surface;" (B) was "dry in the middle, but on every side the water had penetrated about 3 in. and had much weakened the block;" (C) was "wet quite through, and was very easily broken up, the water having been able to percolate continually through the block, and having dissolved much of the lime."

The other three blocks were kept in fresh water for twelve months "with exactly similar results as to penetration of water and strength of blocks," but the water in which block (A) was immersed "remained clear," that containing (B) "became milky and turbid from the formation of carbonate of lime," and that containing (C) "became quite white, and . . . . the whole block was covered with crystals of carbonate of lime, $\frac{1}{4}$ in. to $\frac{1}{2}$ in. in thickness. The lime had been gradually dissolved, and crystallised on the surface in the form of carbonate of lime."

* *Proceedings of the Inst. C. E.*, vol. cvii. (1891-2), part i.

Another experiment, which Mr. Bamber made, corroborates the foregoing results. A box measuring 18 ins. each way and containing, therefore, 5,832 cubic inches, was completely filled by the mass of concrete which resulted from the mixing of the following ingredients:—1,296 cubic inches Portland cement, 2,592 cubic inches sharp sand, 5,184 cubic inches shingle, and 30 lbs., or 829 cubic inches water. These ingredients, not including the water, have an aggregate measurement of 9,072 cubic inches, but on being mixed together the voids in the larger material were filled by the smaller to such an extent that a shrinkage of 3,240 cubic inches took place. Exactly the same quantities of cement, sand, and shingle were mixed with 15 lbs., or 415 cubic inches, of water, with the surprising result that the box would only contain seven-eighths of the mixture; in other words, the ingredients, on being mixed together, shrank only about 2,407 cubic inches. The voids or interstices in the latter concrete therefore exceeded those in the former by about 833 cubic inches.

This and the preceding experiments show that concrete mixed with its full quantity of water is more dense, and therefore less permeable to water, than concrete made with an insufficient quantity.

This conclusion is verified by French experiments; M. Alexander found that mortar gauged with insufficient water, set more rapidly, was more porous, and offered less resistance to the action of sea-water, than mortar gauged with either the normal or an excessive quantity of water; an excessive quantity greatly retarded the setting, but yielded eventually the full measure of strength.

Effect of Quantity on the Strength of Concrete.—The average compressive strength at the age of 28 days, of $1\frac{1}{2}$ inch cubes of Portland cement and normal sand (1 to 3), was ascertained by Mr. Carey to be 1,679 lbs. per sq. in. when 20 per cent. of water was used, and 1,425 lbs. when only 10 per cent. was used. The strength of the cubes containing the full quantity of water was therefore 18 per cent. more than that of the other cubes.

LOSS BY ABSORPTION.—But it does not follow that cement will set to the best advantage, even when the right quantity of water is used; for in many cases, no precautions are taken to prevent the loss of the water before it has done its work. Much Portland cement stucco and concrete is ruined, because its moisture is absorbed by the dry surfaces with which it comes in contact, or is evaporated by the heat of the sun, or abstracted in other ways. One instructive instance of this will suffice. "Some Portland cement stucco was one day applied to three brick walls inside a room; on one wall with the greatest success, on another with only partial success, whilst on the last it was an utter failure, becoming perfectly rotten and crumbling away. . . . . The simple explanation was that the wall on which the stucco succeeded best was quite new and damp; that on which it partially succeeded, being an outer wall, was slightly damp; whilst that on which the stucco became rotten, was an old internal wall, and of course quite dry."*

In many cases, the injurious loss of moisture by evaporation is prevented by covering the concrete for a week or more with a shallow pool of water, or with a layer of sand or sawdust kept continually moist, or with straw, sacks, &c., which protect the concrete from the direct action of the sun's rays and of wind.

Again, all aggregates are more or less absorbent, and some of them, especially coke-breeze and the like, if used dry, greatly injure concrete made with them by drawing from the mixture the water necessary for the proper hardening of the cement. In order to prevent this, all aggregates ought to be moistened before being made into concrete; the process of washing the aggregate effects this, and is, therefore, most useful and economical when carried out immediately before the aggregate is mixed with the cement. This proper moistening of the aggregate is a matter of great importance.

CONCRETE DEPOSITED IN WATER.—Table I. page 20 showed that briquettes of various hydraulic limes and sand

* *The Architect*, Sept. 20, 1873.

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kept in water (*after having set in air*), were from 30 to 105 per cent. stronger than similar briquettes kept in air, while the strength of Portland cement was approximately the same in both cases. Concrete, however, *deposited* in water is invariably weaker than concrete which has set in air.

Impurity of Water and its effects.—Mud of any kind, held in suspension by the water, is detrimental to the concrete made with it. Mr. Carey found that briquettes made with a certain kind of cement, mixed with 20 per cent. of distilled water, required three hours to set, and at the end of seven days had an average tensile strength of 480 lbs. per sq. inch, while other briquettes, similar in every respect, except that 1 per cent. (by volume) of dried and finely-powdered Thames mud was mixed with the water, took four hours to set, and broke with 411 lbs., that is to say, over 14 per cent. less than those mixed with pure water.

Water containing organic matter is also more or less injurious, and consequently green and stagnant pools ought not to be used for mixing in concrete.

But not only is mud or other matter held in suspension by the water injurious to the cement with which it is mixed; matters dissolved in the water also may prove harmful. Such substances as sugar, soda, and salt are, in frosty weather, sometimes dissolved in the water used for making concrete, either for the purpose of lowering the freezing point of the mixture and so allowing it to be manipulated at a time when fresh water would be frozen solid, or for the purpose of preventing or, at any rate, minimising the damage which might possibly be caused to the concrete by frost coming before it had set sufficiently. Until there is more information on the subject, we shall be justified in believing that Portland cement is ultimately strongest when mixed with distilled water and nothing else; all additions, whether of mud, or sand, or ordinary aggregates, or of sugar, salt, or other dissolved substances, are a source of weakness. The use of sugar, however, with fat limes, and probably with hydraulic limes and natural cements, is attended with advantage.

The increase of strength caused by adding a small quantity of sulphuric acid to fat and hydraulic limes has already been shown in the chapter on Selenitic limes, and the effect of adding it to Portland cement has also been mentioned.

In 1891 Col. Seddon drew attention to a curious instance of the destruction of a concrete foundation by a spring of water, which welled up under it. The water, which was brackish and impregnated with red oxide of iron, affected the lime in the cement and was affected by it, so that the cement would not set, and the nature of the water was changed. When holes were cut in the concrete, the spring-water rapidly filtered up into them, and, instead of being reddish, was green at the bottom and clear at the top, and both "smelt and tasted strongly of sulphuretted hydrogen, the presence of which was also proved by chemical analysis." Even blocks of good concrete (mixed with sea-water), when placed on the damp rotten foundation, soon became rotten themselves.

Experiments were then made by Col. Seddon, with the somewhat curious result that concrete mixed with the *spring*-water set properly, but concretes (varying in composition from 1 cement and 3 aggregate to 1 cement and 9 aggregate), mixed with the *green* water, were quite rotten. The rottenness was evidently caused by the action of the green water and the oxygen of the air.

Had the concrete been quite impervious, it is probable (from experiments by Mr. Dyckerhoff) that no damage would have been done by the spring of water. Cement-mortar, which has been mixed with iron-water, has been found by the writer to cause the formation of black stains on ashlar, although the mortar itself has apparently remained perfectly sound.

Sea-water.—The strength of Portland cement does not differ very much whether it be gauged with fresh water or with sea-water. Apparently the sea-water briquettes are the stronger at early dates; but after a few months the fresh water ones take the lead, and continue to give the best

results. It must be said, however, that experiments are somewhat contradictory on this point.

Mr. M. J. Powers in America has tested 3,500 briquettes made from seven kinds of cement, with the object of ascertaining the influence of sea-water. He found that the strength of both Natural and Portland cements mixed with salt-water was, at the end of one month, 30 per cent. more than when mixed with fresh water, but this gain of strength was found to vanish during the second month in the natural cements, and during the third month in Portland cements; thenceforth the fresh-water briquettes having the advantage. His conclusions are that "there can be no doubt that cement mixed with sea-water gains considerably in strength during the first few weeks, but that it does not hold out is clearly shown by these results. . . . The gain also seems to be greater and more permanent with the Portland than with the natural cements. The effect of using a 10 per cent. solution seems not so good as with a 3 per cent. solution."

Some experiments by Mr. Carey show little variation in the strength of Portland-cement briquettes, whether gauged with—1, fresh water; 2, half distilled water and half sea-water; 3, one-quarter distilled water and three-quarters sea-water; 4, sea-water, 25 per cent. evaporated; 5, sea-water, 50 per cent. evaporated. The greatest difference at one month was 3·2 per cent., 4 being strongest; at two months 4 per cent., 4 again strongest; at three months 26 per cent., 5 being strongest and 4 weakest; at six months 35 per cent., 1 strongest and 4 weakest; at nine months 8·2 per cent., 5 being strongest and 4 weakest; and at twelve months, 27 per cent., the following being the tensile strengths in lbs. per square inch at this date,—1,—678; 4,—605; 2,—592; 3,—575; and 5,—495. It will be seen that the fresh-water briquettes come to the front at the end of a year, but the results of the various tests are so strange and irrational that we cannot attach much importance to them. The tests by Mr. Powers are more likely to be accurate.

In the case of hydraulic limes, sea-water, according to M. Alexander, exerts a deteriorating influence.

Cement gauged with sea-water sets more slowly than with fresh water. Sea-water has the advantage of having a lower freezing-point than fresh-water, and work can, therefore, be carried on with it at times when fresh-water would be frozen. It ought not, however, to be used in the walls of buildings or in stucco, as it has the property of attracting moisture, and of causing an efflorescence on the surface of the material with which it has been mixed. Again, sea-water ought not to be used in concrete which will come in contact with ammonia, as in the paving of stables, shippens, chemical works, &c. But for foundations, retaining walls, and similar work sea-water may be used instead of fresh, if more convenient.

WARM WATER.—Sometimes, especially in winter, warm water is used for concrete. It has the effect of causing the cement to set sooner, and for that reason it may in certain cases, be employed.

SEWAGE.—Portland-cement concrete is now extensively used for sewers and sewage tanks, and is well adapted for these purposes, but the concrete must be allowed to harden for three or four weeks before the sewage is brought into contact with it. Strong sewage seriously injures new concrete and cement mortar.

CHAPTER X.

SAND.

Importance—Effect—Definition and varieties of sand—*Siliceous*, *Calcareous* (Table XIII.), and *Igneous* (including puozzolana, trass, &c.)—Characteristics of good sand—(1) *Cleanliness*, (2) *Coarseness* (Table XIV.), (3) *Sharpness*, (4) *Hardness*, and (5) *Durability*—Substitutes for sand (Table XV.).

Importance.—We have, at some length, considered the various limes and cements which are used in concrete. The remaining ingredients now call for notice, and at the outset we must say that the disintegration and rottenness of concrete are often due, not to the lime or cement, but to the aggregate. An instance in point is recorded in *The Engineer* for May 30, 1890; about a thousand concrete blocks, which had been made for the Shillamill Viaduct on the Plymouth, Devonport, and S.-W. Junction Railway, were perfectly useless, and at length it was discovered that the sand which formed part of the concrete contained mundic,* a mineral washed down the stream from an arsenic mine, and this had totally destroyed the setting properties of the cement. Other instances could be quoted to show the importance of the aggregate.

Effect.—The addition of sand to cement-paste has two effects: it weakens the mortar and retards the hardening of the cement, both in air and in water (see fig. 3, p. 74). To pastes of fat and feebly-hydraulic limes, however, the addition of a certain amount of sand quickens the hardening of

* Mundic (known also as "iron-pyrites") contains 46½ parts of iron and 53½ parts of sulphur; the injurious effect of large quantities of sulphur on Portland cement has been already shewn.

the mortar in air, and increases its ultimate strength, but this at the best is very little. The more hydraulic the lime or cement is, the less is the advantage of adding sand except for the sake of economy. Neat cement is stronger in every way than any mixture of cement and sand. Table I., p. 20, shows the diminution in tensile strength caused by mixing increasing quantities of sand with various limes and cements.

Rule for Finding Strength of Mortar.—An empirical rule for finding the approximate strength of different kinds of Portland-cement mortar, when the strength of the neat cement is known, may be expressed thus :—

$$\left.\begin{array}{c}\text{Ultimate strength}\\ \text{of neat cement}\end{array}\right\} \times \frac{\text{vol. of cement} + 1}{\text{vols. of sand} + 2} = \text{ultimate strength of mortar.}$$

Thus, if the tensile strength of a neat cement be 1,000 lbs. per square inch at (say) 12 months, the strengths of mortars made with it may be expected to be as follows :—

1 to 1 mortar . . .	$1{,}000 \times \frac{1+1}{1+2} = 666$ lbs.	per sq. in.
1 to 2 „	$1{,}000 \times \frac{1+1}{2+2} = 500$ lbs.	„
1 to 3 „	$1{,}000 \times \frac{1+1}{3+2} = 400$ lbs.	„

The rule does not hold good for mortars containing more than 6 or 7 volumes of sand.

Definition and Varieties of Sand.—" Sand is, in general, a loose aggregation of water-worn particles, arising from the disintegration of pre-existing rocks or other mineral matter. It is generally composed of quartz-grains (quartz being one of the hardest of simple minerals, and longest resisting the processes of attrition); but it may also consist of the particles of shells, corals, &c., hence such terms as shell-sand, coral-sand, iron-sand, and the like.

The minute particles thrown out by volcanoes, and produced by explosive force and attrition, are spoken of as volcanic sand." *

SILICEOUS SAND.—The sands, most commonly employed in mortar and concrete, consist of quartz-grains, but are distinguished as "pit-sand," "river-sand," and "sea-sand," according to their origin. The two last names refer to the sand lying in the present river-beds or on the sea-shore, while the first refers to sand deposited ages ago in long-vanished waters and now forming part of the dry land. Instead of these, "sands" crushed from different kinds of rocks are frequently used.

CALCAREOUS SAND.—Calcareous sand yields somewhat better mortar than siliceous sand, on account of the chemical affinity of the former with the constituents of the lime or cement. In all probability, also, physical as well as chemical causes contribute to the advantage, the siliceous sand being as a rule denser and smoother than the other.

Experiments have been made by Mr. Charles Colson on mortars composed of equal parts of Portland cement and sand of different kinds; the results are given in the following table:—

TABLE XIII.—COMPARATIVE VALUE OF SANDS (POROUS AND NON-POROUS).

Nature of Sand.		Tensile Strength at 28 days in lbs. per sq. inch.	Ratios.
POROUS	Crushed Portland Stone .	311·50	100
	,, Brick...............	298·60	96
NON-POROUS	Crushed Granite ...	264·03	85
	Sand†	241·22	77

The Portland cement used in the foregoing experiments had a tensile strength, neat, of 438·11 lbs. per square inch

* Dr. Page's "Advanced Text-Book of Geology."

† It is not stated whether this was pit-sand or river-sand.

at 28 days, and the result is in each case the average of 56 tests. More water was required to gauge the briquettes made with the porous "sands" (crushed Portland stone and crushed brick), than with the non-porous sands.

Tests by Lieutenant Innes (Table XV., p. 115) also place crushed Portland stone before sea-sand and pit-sand, and tests made by Mr. Grant on the crushing strength of concrete-blocks (Table XVI., p. 127), show that Portland stone is a better aggregate than granite, slag, ballast, &c.

Igneous Sands, &c.—Igneous rocks are classified as *Granitic*, *Trappean*, and *Volcanic*, the last being the name applied to those igneous rocks which are of recent formation. This *Volcanic* group is interesting to the architect and engineer, because it includes *puozzolana* (from Puozzoli, near Naples), *trass* (from Rhenish Germany), and other substances of similar nature, which confer a quite considerable amount of hydraulic energy on pastes of fat lime. Such substances are now seldom used in England, but prior to the introduction of Roman and Portland cement they were in great demand for works in water. Smeaton used puozzolana mixed with Aberthaw lime in the mortar of his Eddystone lighthouse. Both Vitruvius and Pliny describe its use among the Romans.

The chief ingredients of these volcanic earths or sands are silica and alumina (the former largely preponderating), and these, as we have already shown, are the ingredients which give to most limes and cements their hydraulic energy. Into the detailed composition of puozzolana, trass, &c., and the method of using them, it is not necessary for us to enter, seeing that they have fallen almost out of use in our country, but we must say a word or two about the statement which is frequently made, especially in advertisements, that cement will bind a much larger quantity of granite-sand than of any other sand.

Doubtless this statement rests on the fact that certain igneous earths do confer hydraulic energy on lime. Gillmore states that the sand of "certain grauwackès, psammites, granites, schists, and basalts" confers a small amount

of hydraulic energy, but that they are improved by calcination; they can, he adds, be used in larger proportion than other sand for mortars, when time can be allowed for the sand to develop its hydraulic properties before the mortar is immersed. It will be noticed that Gillmore does not say that *all* granites, &c., have this property, but only *certain* of them, and more recent researches seem to show that fewer of these sands confer hydraulic energy than Gillmore thought.

A French authority, M. Alexander, after numerous careful experiments, declared, in 1890, that *calcareous* sand yielded the strongest mortar, and that *siliceous*, *granitic*, and *silico-calcareous* sands (crushed from rocks, not natural sands) gave results practically equal to one another; he deprecated the use of argillaceous material instead of sand.

In many parts of Japan a decomposed granite sand is found, the coarse, gritty part of which has, according to Dr. Takayama, no beneficial effect whatever on lime, but the fine, yellowish powder, resembling "china clay of good quality," and forming less than one-fourth of the total quantity of the sand, does confer hydraulic properties.

"Some felspathic granites," says Dr. Page, "like those of Devon and Cornwall (Cornish stone), are easily decomposed when exposed to the weather (or artificially ground down), and in this state produce a fine impalpable clay (silicate of alumina,—silica, 60; alumina, 40), known as *kaolin* or China clay, and largely employed in the manufacture of the finest pottery and porcelain." The yellowish powder in the Japanese sand just alluded to is evidently similar to the clay produced by the decomposition of these felspathic granites, and, bearing in mind the constituents of hydraulic limes and cements, we can quite understand that the addition of silicate of alumina in this impalpable form may confer upon limes more or less hydraulic energy. Indeed, a white cement, which has the same general characteristics as Portland cement, but with only about one-half its tensile strength, can be made by grinding together three parts of chalk and one of kaolin, burning at a red heat, and again grinding.

On the other hand, the fine dust formed in crushing syenite and other granite rocks, has been found by experiment to have a weakening effect on mortars, just as other fine dust or mud has.

From this it will be seen that only certain kinds of igneous rocks, and these only when decomposed or ground to an impalpable powder, confer hydraulic properties upon lime, and not ordinary granite, whether in the form of grains or of dust. We may assume that those granites which weather best as building-stones will confer the least benefit on limes and cements.

Apart, however, from all questions of hydraulicity, granite-sand forms excellent concrete, the grains being irregular and durable, and not rounded or water-worn as are the grains of siliceous sands. Mr. Henry Reid, in his "Practical Treatise on Concrete," gives the results of tests showing that granite sand yields a mortar about 15 per cent. stronger at 28 days than that obtained with Thames sand.

Characteristics of Good Sand.—The characteristics of good sand are :—1, cleanliness ; 2, coarseness ; 3, sharpness ; 4, hardness ; and 5, durability.

(1) *Cleanliness.*—Sand should be free from clay and organic matter, and, if the presence of these be suspected, the sand should be thoroughly washed, as they prevent, to some extent, the proper hardening of the cement. Mr Grant, in 1862–3, found that, at all ages up to twelve months (and the experiments were not carried further), briquettes made with loamy pit-sand were considerably inferior to those made with clean pit-sand. His experiments on briquettes one month old gave the following ratios of strength :—1 to 1 mortar, clean sand 100—loamy sand 83 ; 1 to 2 mortar, clean 100—loamy 78 ; 1 to 3, 100—74 ; 1 to 4, 100—84 ; and 1 to 5, 100—64. Briquettes twelve months old yielded the following ratios :—1 to 1 mortar, clean sand 100—loamy 81 ; 1 to 2, 100—87 ; 1 to 3, 100—84 ; 1 to 4, 100—77 ; and 1 to 5, 100—77.

Roughly speaking, therefore, the presence of loam reduced the strength of the mortars about 20 per cent. Table III., p. 23, confirms the results obtained by Mr. Grant, and shows the increased cost, per unit of strength, of mortars containing loam.

On the other hand, some experiments by Mr. E. C. Clarke, of Boston, with briquettes of cement and sand, the latter containing about 10 per cent. of loam, showed that "at one month the breaking loads were only about one-half what they would have been had clean sand been used, but at six months and one year little difference was observable." The knowledge that clean sand gives twice as good results at one month as loamy sand, is quite enough to preclude the use of the latter.

Mr. Clarke also found that the presence of clay "in moderate amounts" does not weaken cement-mortars; but this is certainly contrary to the general belief.

Sand from roads, pits, and sluggish streams or ditches must be looked upon with suspicion, as it will in all probability contain fine mud, or clay, or organic matter; but sand from the beds of quickly-flowing streams may generally be accepted as clean enough, as the loam and clay will have been washed away by the stream. Sand from quarries is also good in this respect. Further, sand should not contain any mineral substance or colouring matter which would injure the strength or appearance of the concrete, such as iron, salt, coal-dust, &c. Some pit-sands in Lancashire cause the formation, in moist Portland-cement concrete, &c., of black drops of water, like ink, and these have a bad effect on the appearance of the work.

The salt in sea-sand does not appear to have any appreciable effect on the strength of the mortar or concrete in which it is used, but it has a tendency to attract moisture and cause efflorescence on surfaces exposed to the atmosphere. Washing the sand in fresh water may lessen this tendency a little. Many concrete houses have, however, been built with material taken direct from the sea-beach without any ill-effects, provided that the exterior is covered

with a stucco of cement, mixed with clean pit or river sand.

(2) COARSENESS.—This characteristic has more influence on the strength of mortar and concrete than architects usually think. Many experiments have proved that fine sand makes weaker mortar than coarse. The explanation of this probably lies in the fact that the smaller the grains are in a certain quantity of sand the greater is the superficies over which the cement-film has to be spread. For instance, in a cubic inch there are, roughly speaking, about 8,000 grains of sand one-twentieth of an inch in diameter, or about 27,000 grains one-thirtieth of an inch in diameter; the total superficies of the former grains will be $(\cdot 05 \times \cdot 05 \times 6 \times 8{,}000 =)$ 120 square inches, and of the latter $(\cdot 0\dot{3} \times \cdot 0\dot{3} \times 6 \times 27{,}000 =)$ 176 square inches. In other words, the grains in one-and-a-half measures of the coarser sand will have only about the same superficies as in one measure of the finer.

The following table gives the results of two series of tests carried out by Mr. Grant in 1878–9. The cement was sifted through a sieve with 2,580 meshes to the square inch, and was made into briquettes with three parts of sand (by weight); all the briquettes were kept in water. Each figure is the average of ten tests, the result being given in lbs. per square inch:—

TABLE XIV.—COMPARATIVE VALUE OF SANDS (COARSE AND FINE).

No.	Composition of briquettes.	Sand tested by sieves.	At 28 days.	60 days.	91 days.	182 days.	273 days.	364 days.
		Nos.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
	First Series—							
1	1 cement to 3 sand	20—30	78·5	113·9	116·9	142·3	178	205·5
2	ditto.	10—20	137·1	239·5	223	231·5	254·5	251·5
	Second Series—							
3	1 cement to 3 sand	20—30	117·2	134·5	145	156	157·8	213
4	ditto.	10—20	212	236·5	206	253	267·5	273·5

The sand used in the tests numbered 1 and 3 had all passed a No. 20 sieve (400 meshes to the square inch), and had all been retained by a No. 30 sieve (900 meshes to the square inch); for the tests numbered 2 and 4, the sand had passed a No. 10 sieve (100 meshes to the square inch), and had been retained on a No. 20 sieve. The superiority of the briquettes made with the coarser sand is very evident, but it is also evident that the superiority is greatest at the earlier dates. After about two months the strength of the briquettes made with the finer sand gradually approaches that of the coarse-sand briquettes. Thus, the latter are 77 per cent. stronger than the fine-sand briquettes at the age of one month, and 91 per cent. at two months, but they are only 63 per cent. stronger at three months, 62 at six months, 55 at nine months, and 25 at twelve months. It would be interesting to know by experiment whether the more rapid increase of strength by the fine-sand briquettes is maintained until the two mortars are of equal strength. The probability is that such is not the case, but that the finer mortar is permanently weaker.

But whether this be so or not, the coarser sand ought to be used, for, other things being equal, that mortar or concrete which will attain a certain strength in the shortest time is the most suitable. Architects and building-owners cannot afford to wait an indefinite period for concrete to harden; the centres of a concrete floor will probably be struck in a month or less, and if at that time concrete made with coarse sand is 77 per cent. stronger than that made with fine sand, there can be no doubt as to which ought to be used.

Sand containing both coarse and fine grains is better than all fine, and yields mortar little inferior in strength to that made from coarse sand. When only fine sand is available, less ought to be used in proportion to the cement.

The fine sand which is blown about by the wind and formed into sandhills makes bad mortar and concrete; and the fine powder, which is produced by stone-crushing

machines, ought to be washed from the sand and broken stone before these are used, as it has an enfeebling effect.

The property of coarseness needs consideration also in connection with the porosity and permeability of concrete. M. Alexander's experiments educed the somewhat surprising fact that sand, consisting wholly of coarse grains, yields not only a stronger mortar than wholly fine sand, but also a mortar less porous and less permeable to water. A mixture of coarse and fine grains, however, contains less voids, and yields a denser mortar than either coarse or fine grains used separately. The mixture containing the least voids, was found to have coarse and fine grains in the proportion of 6 to 4. A measure of sand, consisting of equal-sized grains of any kind,—coarse, medium, or fine,—contained about 50 per cent. of voids; the mixture, just referred to, contained only 36 per cent.

(3) Sharpness.—The sharper the sand is the better. The angularity of grains helps to bind them together and give them a sort of bond. The advantages of angularity are clearly evident in surfaces subjected to much wear, as paving; from these, round smooth grains are detached much more easily than irregular sharp grains. Sand obtained by crushing hard, compact rock, is very good in this respect; sea and river sand is not so good, but varies very much according to the place where it is obtained.

Experiments made by Mr. Kinipple on two mortars composed (1) of 1 part Portland cement and 1 part sand obtained by crushing sandstone in a Blake's crusher, and (2) of Portland cement and pit-sand in equal proportions, showed the former to be over 50 per cent. stronger than the latter. This was doubtless due to the superior angularity, cleanliness, and coarseness of the crushed sand.

Some sand-grains have sharp edges, but smooth surfaces, while others are rounded but with rough surfaces; experiments have shewn that these two varieties yield mortar approximately equal in strength.

(4) Hardness.—Many sands contain a considerable proportion of earthy grains, which are a source of weakness.

There are some sand-stone, limestone, and even igneous rocks, which crumble almost at a touch, and the grains of which are soft and easily crushed. These ought not to be used. The harder the rock, the stronger will be the sand obtained from it.

(5) DURABILITY.—It would be folly to make concrete walls with an aggregate which would soon succumb to the action of the atmosphere. There is, however, little fear of any natural sand being deficient in durability, but the sand obtained by crushing certain limestones and sandstones, which weather badly as building stones, ought to be carefully examined before its use is permitted. As a rule a hard-grained sand will prove durable.

SUBSTITUTES FOR SAND.—It is not always that natural sand, or sand crushed from natural rock, can be obtained. Ground brickbats or pottery, burnt and ground clay, slag-sand, coke-breeze from gasworks, smithy-ashes, &c., may be used as substitutes.

Ground *brickbats,* if well-burnt and free from dirt, old mortar and lichens, make good mortar. *Clay* should be thoroughly burnt, or it will irretrievably spoil all mortar or concrete in which it may be mixed. The dust of brick-bats and burnt clay is considered (on rather slight evidence it must be said), to confer a small amount of hydraulic energy on fat limes. *Coke-breeze* is not to be recommended for use in walls, ground-layers, and foundations, on account of its porosity and weakness. *Smithy-ashes* and *foundry-sand* have been recommended by some authors but do not always give good results. *Soot* ought to be avoided.

A series of experiments of considerable interest were made by Lieutenant Innes, R.E., and read to the *Institution of Civil Engineers.** Briquettes were made of Portland cement and sand, or substitute for sand, in the proportion of 1 to 2, and were kept in water until tested. All grains exceeding one-twelfth of an inch were removed from the various sands, &c., but apparently no attempt was made to

* *Proceedings*, vol. xxxii. 1870-1.

TABLE XV.—COMPARATIVE VALUE OF SANDS AND SUBSTITUTES FOR SANDS.

No.	Nature of Sand, &c.	Voids per cent.		Shrinkage per cent.	Grains above $\frac{1}{50}$ in. [per cent.]	Tensile Strength in lbs. per sq. in.			
		Dry.	Wet.			Three Weeks.	Proportional value of "Sands."	Three months.	Proportional value of "Sands."
1	Neat cement	—	—	—	—	450	—	529	—
2	*Sea Sand*, roughish and uneven grain, chiefly siliceous, clean	38	34	6	94	140	52·4	249	70·1
3	*Sea Sand* (*drifted*), siliceous, clean	43	36	11	8	60	22·3	193	54·3
4	*Pit Sand*, containing small shells, &c., grains of unequal size, siliceous	32	19	16	15	108	40·1	248	69·8
5	*Pit Sand*, grains smooth and uniform, siliceous, clean	41	34	11	76	94	34·9	175	49·8
6	*Portland Stone Dust*, roach and whitbed, grains rough and irregular, clean	46	34	18	56	165	61·3	254	71·5
7	*Smithy Ashes*, containing much unburnt coal-dust, grains rough and irregular	64	52	25	56	38	14·1	91	25·6
8	*Clay Ballast*, burnt and ground, pale brick-red colour, rough, uneven grain, containing much dust	50	40	17	40	269	100	355	100

remove the fine dust in any of them. The results of the tests are given in the foregoing table, and also the proportional value of the "sands" at the two ages, at which the briquettes were broken. The mortars made with clay-ballast and smithy-ashes, were apt to shrink and crack.

Lieutenant Innes's experiments showed, therefore, that the clay-ballast gave the best results, and the other sands, &c., followed in this order,—Portland stone-dust, ordinary coarse sea-sand, rough pit-sand, smooth pit-sand, drifted sea-sand, and, lastly, smithy-ashes.

If the table be considered in the light of our remarks about the essential characteristics of good sand, the differences between the various sands and substitutes will be easily explained.

CHAPTER XI.

AGGREGATES.

Selection—Gravel and Shingle—Broken stone: 1. *Igneous Rocks;* 2. *Flints;* 3. *Sandstones;* 4. *Limestones;* 5. *Slates*—Broken bricks, &c.—Burnt clay, &c.—Coke-breeze, &c.—Slag—Shells—Sundries—Resistance to fire—Strength (Table XVI.)—Resistance to wear.

SELECTION.—The selection of an aggregate is largely influenced by the locality in which the work is required, and by the use to which the concrete is to be put. The aggregate which is most easily available and most economical is usually employed. It would be a waste of money to specify burnt clay for a building on the site of which suitable stone could be obtained, while the clay would have to be brought there at considerable expense; for any reasonable inferiority of aggregate can be remedied by using with it a proportionately larger quantity of cement.

The remarks about the cleanliness, angularity, hardness, and durability of sand may be applied with equal truth to the aggregates. But a little further information about the more common kinds of aggregate will be useful.

The number of different materials which have been used in concrete is very large. We may mention gravel, shingle, broken stone of various kinds, broken brick and pottery, burnt clay and shale, coke-breeze, slag, shells.

GRAVEL AND SHINGLE.—Ordinary gravels contain a considerable quantity of sand, varying, perhaps, from one-third to one-half the total volume. This may advantageously be sifted out, so that the several ingredients of the concrete can be accurately measured. Gravel from pits and from sluggish streams ought to be washed before being used, as

the former will probably contain clay in considerable quantities, and the latter may be coated with fine mud or slime, or may contain an excessive amount of very fine sand; but gravel and shingle from some parts of the sea-beach and the beds of rapid streams do not need further cleaning.

For rough concrete in ordinary foundations, &c., gravel forms a good and economical aggregate, as it may be used in many instances with little or no preparation. The larger rounded pieces in shingle, &c., should be broken, so as to give them a certain amount of angularity, in order that the cement may adhere to them more firmly, and that they may be wedged and bonded together. Shingle, &c., which contains large irregular pieces, makes stronger concrete than that consisting entirely of smaller pieces rounded by attrition.

Opinions differ as to the value of gravel and similar material as an aggregate. Some persons go so far as to say that it is the best of all aggregates, while others loudly condemn it. The fact is that such material, from its hardness and durability, is useful in foundations and walls, where the concrete is subjected mainly to compression; but in floors and other places where it is subjected to transverse stress, it does not form a good aggregate, because of its great weight, the smoothness and roundness of its stones, and the small resistance it offers to the action of fire.

Of two kinds of gravel or shingle, that one is best, other things being equal, which has the smallest interstices; for in this case a smaller quantity of sand is required with the cement to produce solid concrete, and this is important because the strength of concrete depends largely on the strength of the mortar (*i.e.*, the cement and sand) in which the gravel, or other material, is embedded.

The gravel obtained from the Thames and usually known as Thames ballast, is good aggregate for foundations and walls, being usually fairly clean and irregular, and containing sand of good quality.

All gravel is more or less rounded by attrition, and this of course is a disadvantage. Usually, also, it is not

porous enough to admit of the best adhesion of the cement to its surfaces.

Broken Stone.—A great many kinds of stone have been used as aggregates in concrete,—granite and other igneous rocks, flints, sand-stones of various kinds, limestones, &c. On the whole, limestones seem to give the best results, probably on account of a slight chemical action taking place between them and the cementing substance.

(1) Igneous Rocks.—Igneous rocks are largely used as an aggregate, especially for concrete exposed to much wear, as in the facing of break-waters, dock-walls, coping, and other sea-works. They are almost invariably used in the manufacture of artificial stone, artificial flags, and the best kinds of *in sitû* paving.

Igneous rocks are classified as *Granitic*, *Trappean*, and *Volcanic*, but no examples of the last occur in the British Isles.

Ordinary granite consists of crystals of felspar, quartz, and mica, and is found extensively in Scotland. There are several varieties, such as syenite, and syenitic granite (containing hornblende, and quarried in Leicestershire, Guernsey, &c.), and porphyritic granite (containing large and independent crystals of felspar in addition to the small ones contained in the general mass of the rock, and quarried at Shap in Westmoreland and at several places in Cornwall and Devonshire).

Trap-rocks are of many kinds, the more crystalline varieties, such as basalts and green-stones (or whinstones), being most suitable for aggregates in concrete; some of the earthier varieties confer a certain amount of hydraulic energy on limes and cements. The Giants' Causeway in Ireland, and Fingal's cave in Staffa, are well-known examples of basaltic rocks, and other trap-rocks are found in Derbyshire, Cumberland, North Wales, &c. Mr. Thomas Dyke states that whinstone withstood the grinding-test for wear much better than either granite or shingle, blocks of each being applied under the same pressure to the face of a revolving grindstone.

Granitic and Trappean rocks of various kinds can be obtained from many quarries, broken by machinery into various sizes suitable for concrete. They form an excellent aggregate for foundations, walls, and paving, being hard, angular, and durable. For floors their weight is a disadvantage, and so also is their great liability to crack or disintegrate under the action of fire.

(2) Flints.—Flints are lumps of grey or black silex, found, usually in horizontal layers, in beds of chalk. They are of all sizes up to a foot or more in diameter, and, when dry, are extremely hard and refractory. Owing to their glassy surfaces they do not form one of the best of aggregates, but broken into suitable sizes they can be used in foundations and walls; their great weight, and their tendency to "fly" under the influence of fire, render them unsuitable for floors. If the flints have been taken from land under cultivation, they ought to be washed before being used.

They are extremely durable, being practically unaffected by atmospheric changes and impurities.

(3) Sandstones.—It is impossible to mention all the sandstones which are suitable for concrete. A few general observations must suffice. Those sandstones which yield durable building stones will usually yield good aggregates, while those which are friable and which favour the growth of vegetation upon them will not. Sandstones vary considerably in weight and in strength, and this must be taken into consideration; the strongest and heaviest may be used in foundations, walls, and paving, and lighter varieties may be used in floors. All sandstones are apt to crack and split under the influence of heat, although they are not as much affected by it as are granites and limestones. It is not wise, however, to use them in floors which are intended to be fire-resisting. The degree of porosity of the stone has also an influence on the ultimate strength of the concrete; the dense stone which splits into thin layers with smooth mica surfaces, such as Yorkshire flags, will not yield as good concrete as a rather more porous rock. But care must be

taken that the stone, especially the porous varieties, is well soaked with water before the cement is mixed with it, otherwise the aggregate will absorb the moisture from the cement, and the hardening of the latter will be prematurely stopped.

Old building materials often furnish a convenient and economical aggregate, but, as a rule, they will be much improved by being washed after they are broken.

(4) LIMESTONES.—The great variety of limestones precludes a detailed description of them. The remarks about the strength, weight, and porosity of sandstones are applicable to limestones. A large amount of fine dust is produced in crushing limestone, and as this weakens the concrete it ought to be washed away.

Kentish Rag is a dense, hard, and durable stone, and is often used in concrete for foundations, &c.; Portland stone, and some of the harder varieties of Bath stone, yield excellent aggregates; chalk has also been used for common work, but it cannot be recommended, as it requires careful manipulation and does not attain to the strength which good concrete ought to possess. Marbles also will prove suitable for aggregates, and, in fact, any material of sufficient strength and durability, and to which the cement will adhere, may be used.

Many of the harder varieties of limestones and marbles are used for the face-concrete or finishing-surfaces of paving, curbs, &c., in the same way as crushed granite, and, although they are not equal to the latter in durability, they furnish an extremely hard surface, capable of taking considerable polish.

As we have already stated, limestone is easily affected by fire; sometimes the limestone facing of buildings has been entirely burnt away, while the brick backing has remained standing.

(5) SLATES.—Broken slates, the refuse of slate quarries, may also be used in concrete, but they are too dense and laminar to make really good work.

BROKEN BRICKS, &c.—Broken bricks of various kinds,

roofing tiles, retorts, and pottery furnish extremely useful aggregates. They have, in the process of manufacture, been subjected to great heat, and are therefore less liable to change of form under the influence of fire; for this reason they are especially valuable for the concrete of floors, &c., which are intended to be fire-resisting. Broken fire-bricks have been specially recommended for this purpose, but some of them have not much strength. Many kinds of bricks, too, are lighter than some kinds of stone, and this is worthy of consideration in floors, but the crushing strength of the latter will, as a rule, be greater than that of the bricks.

The porosity of most bricks is a point in their favour, as this facilitates the adhesion of the cement to their surfaces, but care must be taken that the bricks are soaked with water before they are made into concrete. Experiments have shown that dry, soft place bricks, joined with lias lime mortar, can be separated with only one-half the force that is required to separate hard grey stocks similarly united; the figures being 18 lbs. and 36 lbs. per square inch respectively at the end of one month.

Old brickwork and tiles from buildings, pottery-refuse, &c., usually require thorough washing before they are fit for use.

Some experiments on concrete arches carried out by Mr. C. Colson,* showed that the arches composed of Portland cement, sand, and broken bricks were more than 50 per cent. stronger than similar arches of Portland cement, sand, and screened harbour shingle, the proportions in all cases being the same, namely, 1, 3, and 6. The superior strength was "evidently due to the more absorbent and angular character" of the bricks. "The appearance of the fractures in the two cases, *i.e.*, shingle and broken brick, showed a marked difference. In the first case, the strain destroyed the adhesive power existing between the shingle and the matrix; in no instance was a stone observed to be fractured, the casts being, as a rule, clearly defined in the cement. In the second case, the superior adhesive power existing between

* See Table XXIX., p. 288.

the broken brick and cement matrix was manifest; in but few instances had the cement left the surface of the brick, the general characteristic being that of complete disintegration of both brick and matrix."

Bricks ought not to be used as an aggregate in works exposed to the sea, as they have been found to disintegrate under such conditions.

Burnt Clay, &c.—Closely akin to broken brick is burnt clay. This is frequently recommended as a good aggregate, and so it is when the material is clean and good, and the burning is thoroughly carried out. But it is just this thorough and equal burning of the clay which is so difficult of attainment,—especially in contract work. As a rule, some other aggregate can be obtained, which will be of more uniform quality; underburnt clay will make wretched concrete.

The material is usually burnt over a fire of wood and coa or coke, fresh supplies of clay and combustible materia being added alternately as the burning proceeds. Great care, however, is requisite in the burning to insure uniform results. It is not many years since a contractor had to pay 50*l.* for damages caused by the falling of the walls of two concrete cottages, in which unburnt shale and clay had been used as an aggregate.

Burnt ballast should be of a dark red or purple colour; a bright red colour indicates imperfect burning.

Shale, which may be described as a laminated clay or mud, is sometimes burnt and used for concrete in the same way as clay, and has been highly recommended.

Coke-breeze, &c.—Coke and coke-breeze from gasworks, and boiler-cinders from factories, are often used in concrete for floors, roofs, and partitions, where lightness is a desideratum. Concrete made with such aggregates, however, is not as strong as that made with either broken brick or slag or stone; this is accounted for by the inherent weakness of the coke, cinders, &c. The weight of the concrete floor itself is often a very large part of the load which it has to carry, and for this reason, the strength should

always be considered in conjunction with the weight. A light concrete of moderate strength may carry a greater added load than a stronger concrete of great weight. The experiments of Mr. Webster (see Table V., p. 36) go to prove that coke-breeze concrete suffers less from heating and quenching than do concretes made with sand, pumice-stone, fire-brick, and slag.

Some persons have objected to the use of coke-breeze concrete under hearths, as it is a comparatively good conductor of heat, and will, indeed, sometimes become red-hot and char, or even set fire to, adjacent woodwork (see *The Builder* for February 13 and March 19, 1892).

A further advantage of coke-breeze concrete for floors is hat it can be nailed to; floorboards can, therefore, be laid directly upon it, without the necessity of wood joists or fillets, or an intervening space for air (and dirt). But this very lightness and porosity is a disadvantage for walls, foundations, and other places in which it will be subjected to the action of the weather or of water, or where it will be expected to bear great weight. A very porous aggregate requires more cement than one of closer texture, and is not so strong; it is sometimes recommended that porous material should be soaked with thin Portland-cement grout before using, but the cost of this would probably be more than that of getting a better aggregate.

Coke-breeze and similar materials ought to be well wetted before being made into concrete, especially if Roman or other quick-setting cement is used, otherwise they will absorb the moisture from the cement and prevent its proper hardening. And yet, the writer has been recommended to allow the use of ashes in concrete on account of their absorbent nature; the contractor, making the recommendation, argued that the concrete would set more rapidly,—perhaps "dry" would be the better word,—but apparently was not aware that the rapidity of setting would be accompanied by an undesirable loss of strength.

The fineness of coke-breeze is also a factor in lessening the ultimate strength of the concrete. It should not be

used for external walls. As a rule, too, coke-breeze, &c., contain dust and impurities which are a source of weakness, and ought to be washed away.

Slag.—Slag from iron furnaces is used not only for making cement, as already described, but also as an aggregate. It can be obtained from many ironworks and steelworks in the form of sand, and also in sizes, suitable for various kinds of concrete, from $\frac{3}{8}$-in. cubes upwards. It has been often used in harbour and dock-works, especially for face-concrete, for which its hardness and durability render it particularly suitable.

When intended for concrete the slag should not be of hard glassy character, such as that used for road-metal, but should be of open texture, full of pores which permit the adhesion of the cement. This porosity is attained by running the molten slag into water as it leaves the furnace.

Slag-concrete varies much in weight, according to the nature and texture of the slag. Some of it is lighter than Portland-stone concrete, while some is heavier than granite-concrete. On account of its weight it is not usually recommended for floors, although there are the counterbalancing advantages of great strength and resistance to fire. Its hardness renders it very suitable for the surface coats of floors and paving.

Shells.—Shells are also used for concrete in places where they are easily obtained, and in conjunction with gravel, or shingle, or other material, they make good work.

Sundries.—Various materials besides the foregoing have sometimes been used in concrete, and some have even formed the subject of patents. Stuart's "Granolithic" paving is said to contain hæmatite or other iron ore in addition to crushed granite. A recent example is a kind of paving known (in the patent specification) as "Ironcrete," in which pieces of iron are imbedded to give a hard wearing-surface and a good foothold. Sawdust, hemp, and other fibres, coloured glass, and other materials, have been advocated and tried, but have not come much into vogue.

Resistance to Fire.—Mr. Webster's experiments, already

mentioned, seem to show that the resistance to fire of various aggregates is as follows, in order of merit :—1. Coke-breeze; 2. Pumice-stone; 3. Fire-brick; 4. Slag; 5. Sand (and, presumably, gravel, or broken sand-stone of similar composition). The difference between Nos. 1, 2, and 3, is, however, very little.

Mr. Webster also obtained a 4-in. cube of :—1. *Syenite* from North Wales; and a 5-in. cube of each of the following stones—2. *Porphyritic granite* from Westmoreland; 3. *Carboniferous limestone* from Derbyshire; 4. *Portland oolite;* 5. *Sandstone-grit* from Darley Dale, Derbyshire; and 6. *Sandstone-grit* from Bramley Fall, Yorkshire. These cubes were simultaneously placed in a furnace heated to about 2,400 deg. Fahr., but cooling gradually to about 2,000 deg.; they were removed in nine minutes and a quarter. The syenite, at a minute and a quarter, "cracked with a slight explosion, and gradually broke into shelly fragments;" a large corner broke off the porphyritic granite after one-and-a-half minutes, and the remaining portion of the cube "afterwards cracked and crumbled to small fragments;" the limestone began to "calcine at the corners, and in about two minutes began to split up and crumble, the small pieces becoming calcined;" the Portland oolite "stood apparently intact for about three minutes, but a slight tap with an iron rod broke it into pieces, which commenced to calcine;" the two sandstone cubes stood "intact for about four minutes, when they commenced to scale and shell off,"—a small crack had appeared in the Bramley Fall stone in two minutes. From this test, Mr. Webster concludes that of these varieties of stone, granite is the worst, and sandstone the best for resisting the influence of fire.

It has been known for a long time that granite soon succumbs to great heat, and one instance is recorded where "a granite post, 12 in. by 12 in., was reduced to sand by the same fire that burned into a wooden post next to the granite less than 1 in."

Strength.—The tensile strength of briquettes made

with cements and various kinds of sands has been given in several tables, and nothing further need now be said on this point. The crushing strength of concrete made with Portland cement and various kinds of aggregates has been ascertained by Mr. Grant.* Six-inch cubes were made, kept in air for a year, and then crushed, *one test only* being made in each case. The proportions were measured by volume. One-half of the total number of blocks were compressed by beating the concrete into the mould with a small mallet; the remaining blocks were not compressed. The results may be tabulated thus:—

TABLE XVI.—COMPRESSIVE STRENGTH (in tons per sq. ft.) OF PORTLAND-CEMENT CONCRETES HAVING VARIOUS AGGREGATES.

Number.	Nature of Aggregate.	Six to One.		Eight to One.		Ten to One.		Ratios of Strength of Aggregates.
		Compressed.	Not Compressed.	Compressed.	Not Compressed.	Compressed.	Not Compressed.	
1	Ballast	81·6	72·8	54	50	42	32	49·1
2	Portland Stone	162·4	120	132	98	88	76	100
3	Granite.........	122	98	78·4	58	62	46	68·6
4	Pottery	115·2	98·4	88	72	74	56	74·4
5	Slag	92	80	78	56	42	34	56·3
6	Flints	82	62	70	56	60	51·2	56·5
7	Glass	112†	66	72	54·4	50	40	58·3

Too much reliance should not be placed on individual results given in the preceding table, as only one test was made in each case. The average results may, however, be accepted. Taking, therefore, the whole of the six tests of each kind of aggregate into consideration, we find the relative values of the different materials to be as follows:— Portland stone, 100; pottery, 74·4; granite, 68·6;

* *Proceedings of the Inst. C. E.*, vol. xxxii. (1870-1).

† In Mr. Grant's table giving the strength of 6-inch cubes, the figure in this case is 28; possibly it ought to be 18, which would give 72 tons per sq. ft. instead of 112, and this would be more in keeping with the remaining tests with glass, and would relegate it to the lowest place but one.

glass, 58·3; slag, 56·5; flint, 56·3; and, lastly, ballast, 49·1. The roundness and smoothness of the ballast (presumably "Thames ballast"), and the sand and dirt it contained, will account for its low position. The flints also give low results, because of their smoothness and roundness, and, probably, dirtiness, while smoothness and brittleness account for the position of the glass and slag. Granite might have been expected to take a higher place; perhaps it contained a considerable amount of dust. It is also surprising to find Portland stone 25 per cent. better than even pottery; possibly, its angularity, cleanliness, and affinity for cement gave it the premier position.

Similar experiments with broken sand-stone and with coke-breeze would have been valuable to architects.

Mr. S. R. Lowcock found the crushing strength of concrete made of one part Portland cement and 4½ parts clinker (from furnaces burning ashpit refuse) crushed to pass a ¾-in. mesh, and well washed, to be 1120 lbs. per square inch (72 tons per square foot) at the age of fifteen days.

Resistance to Wear.—The durability of concrete paving, curbing, &c., depends largely on the aggregate. This ought to be hard and durable, and at the same time sufficiently rough in texture to permit a firm adhesion of the cement. In England, crushed granite (or rather, syenite) undoubtedly enjoys the highest reputation in this respect; it forms the greater part of nearly all artificial flags and of the best *in situ* paving.

The relative value of different kinds of stone, for paving purposes, was ascertained by a French Public Works Committee in 1880. Their experiments, some of which are tabulated in *The Builder* for November 8, 1890, showed that quartzite was slightly the best material, but was very nearly approached by quartz, porphyries, basalts, and traps. Taking the value of quartzite to be 100, the value of flints would be about 87, of granites and syenites about 76, and of limestones about 63.

Different stones of each kind of rocks vary, of course, greatly. At the Paris Exhibition results of tests of paving

stones were recorded,* which showed that the loss, by abrasion, of igneous rocks, varied from 0·72 to 4·30, and of sandstones from 0·47 (quartzite) to 6.54. The greatest variety will be found among sandstones and limestones, and in selecting aggregates from these rocks, the weight and crushing strength of the specimens under consideration should be compared, as these will give a rough idea of their value. The coarseness or fineness of the grain of the stone has apparently little to do with its resistance to abrasion.

Of the igneous rocks much used in England for paving, some were tested by abrasion, and reported on at the Paris Exhibition. Their relative resistance was as follows :—

Mountsorrel (pink syenite)	100
Guernsey (dark-grey syenite)	85
Aberdeen (light-grey granite)	77
Guernsey (black syenite)	56

All except the last were better than the average of the various igneous rocks tested, but the superiority of the Leicestershire syenite is clearly shown.

* See *The Builder*, Oct. 19, 1889.

CHAPTER XII.

PROPORTIONS OF INGREDIENTS.

Indefinite specifications—Separate measurement of ingredients—Proportion of sand—Of aggregate—Voids in aggregates (Table XVII.)—Voids in sand—Mortar—Solid concrete (Table XVIII.)—Quantity of concrete produced (Table XIX.).

Indefinite Specifications.—The specification of the proportion of the various ingredients in concrete is frequently ill-considered and indefinite. Perhaps the most common fault is the neglect to demand the separate measurement of all the ingredients.

Separate Measurement of Ingredients.—We often see specifications in which concrete is required to be composed of Portland cement, sand, and broken stone in the proportion of 1 of cement to 8 of the other materials, but nothing whatever is said as to whether the sand and broken stone are to be measured separately or not; or the ingredients, perhaps, must be Portland cement, sand, and gravel, proportioned as before, and nothing is said as to whether the sand forming part of the gravel has to be screened from it so that the sand and gravel can be accurately measured.

It may be thought that this is a detail of little importance; a moment's consideration will show that it is of great importance.

In the mixture of Portland cement, sand, and broken stone mentioned above, it would be to the contractor's interest to measure the sand and broken stone together in a box having eight times the capacity of the box in which the cement was measured. He would find that the large box, when filled to the top with broken stone, would con-

tain 30 or 40 per cent. of voids between the stones, and it would be a great saving to him to fill these voids with sand, so that the concrete would really consist of 1 part of cement, and (say) 3 parts of sand, and 8 parts of broken stone, or a proportion of 1 to 11 if the ingredients are taken separately. It needs no great insight to see that a 1 to 8 mixture, in which the proportions are 1 cement, $1\frac{1}{2}$ (or 2) sand, and $6\frac{1}{2}$ (or 6) broken stone, will be stronger than the 1 to 8 mixture described above.

But when gravel is used, there is an added uncertainty; for gravels contain variable quantities of sand, and unless the quantity in the particular gravel specified be ascertained, or, better still, be entirely eliminated, the strength of the resultant concrete cannot be foretold with any approximation to accuracy. Ordinary gravel may contain from 30 per cent. to 50 per cent. of its volume of sand. Two concretes specified to be of 1 part Portland cement and 8 parts gravel, may prove considerably different in strength. If the gravel contain only 30 per cent. of sand, the mortar in the concrete consists of 1 part of cement to 2·4 parts of sand; if the gravel contain 50 per cent. of sand, the mortar consists of 1 cement to 4 sand. The former mortar will be 50 per cent. stronger than the latter, and experiments have shown that the transverse strength of concrete varies very nearly, other things being equal, as the strength of the mortar in which the coarse ingredients are imbedded.

Proportion of Sand.—Two series of most interesting experiments, demonstrating the truth of this statement, were carried out by Mr. Darnton Hutton, at the Amsterdam Canal Harbour Works in 1872 and 1878.* The tests were made because the concrete blocks were not as hard and strong as they ought to have been, and Mr. Hutton came to the conclusion that "where the sand was very fine, the less sand that was used the better."

The first series of tests was made with 1 to 9 concretes containing various proportions of Portland cement,

* *Proceedings of the Inst. C. E.*, vol. lxii., 1879-80, part iv.

shingle, and sand. Taking the transverse strength (at three months) of a mixture of 1 Portland cement + 4 sand + 5 shingle to be 100, we find the strength of a mixture of 1 + 3 + 6 to be 121, of 1 + 2 + 7 to be 225, of 1 + 1 + 8 to be 285, and of 1 + 0 + 9 to be no less than 334.

The second series of tests was made with concretes containing uniformly 1 part of cement and 5 parts of shingle, but various quantities of sand. Taking the transverse strength (at four and a half months) of a mixture of 1 Portland cement + 4 sand + 5 shingle to be 100 as before, we find the strength of a mixture of 1 + 3 + 5 to be 113, of 1 + 2 + 5 to be 184, of 1 + 1 + 5 to be 289, and of 1 + 0 + 5 to be no less than 361.

A comparison of the ratios existing between the various concretes in the two series reveals the fact that the strength depends almost wholly on the quantity of sand mixed with the cement, and not on the amount of coarse material. In other words, the strength of concrete varies, within certain limits, according to the strength of the mortar in which the aggregate is imbedded. It must be noticed that this is true within certain limits only, for, although little difference is noticeable in the strength of sandless concrete, whether it contains 9 parts of shingle or only 5, yet, if the proportion of shingle be increased beyond 9 parts, the limit will soon be reached at which the neat cement becomes too small in bulk to form a film between all contiguous surfaces of the shingle, and dry joints remain, which are, of course, a source of weakness.

Concrete, however, is seldom used in large masses, with a matrix of neat cement, partly because of the cost of such concrete, but also because of its porosity and the greater care required in its manipulation. In Mr. Hutton's experiments, the blocks without sand were full of holes outside, and not by any means homogeneous inside; those containing only one part of sand were also honeycombed, although not to as great an extent as the foregoing. The "shingle,' it must be said, was not "absolutely free from sand."

Fig. 3, page 74, shows graphically the strength of different mortars at different ages. Roughly speaking, it may be said that the strength of Portland-cement mortar 1 to 1 is $\frac{2}{3}$ that of the neat cement, 1 to 2 is $\frac{1}{2}$, 1 to 3 is $\frac{1}{3}$, and 1 to 4 rather over $\frac{1}{4}$. Beyond this, the ratio gives results much too low, but the rule is correct enough within the limits named, and no one would think of using concrete with any greater proportion of sand to cement than 4 to 1. Indeed, a much smaller proportion of sand is invariably used nowadays. It is false economy to use too much sand.

The importance of this point is now so well-known that many engineers consider that even Portland-cement concrete should never have a weaker mortar than 1 to 2, and some object to use a mortar weaker than 1 to $1\frac{1}{2}$. Concrete made with Roman cement should have the cement and sand in equal proportions, or, in any case, the sand should not exceed the cement more than 50 per cent. Lias and Selenitic limes are usually mixed with equal quantities of sand.

But different proportions of sand are required for different purposes; where strength is required the least possible quantity of sand should be used; when imperviousness to water is required, a greater quantity of sand is necessary.

Proportion of Aggregate.—The proportion of aggregate that may be allowed in concrete varies—1, according to the matrix employed, 2, according to the purpose for which the concrete is required, and 3, according to the nature and condition of the aggregate itself.

1. A greater proportion of aggregate may be used with Portland cement than with any other matrix. For, while plaster of Paris and allied cements, and Roman cement, are seldom used with more than 3 or 4 volumes of aggregate (besides sand), Lias limes with more than 4 or 5, and Selenitic limes with more than 5 or 6, Portland cement has frequently been used with 10 or 12 times its bulk of aggregate, and, in the hearting of walls, with a still greater proportion.

2. The purpose for which the concrete is required, is the most important factor in determining the amount of aggregate, but this part of the subject will be left for consideration in succeeding chapters on foundations, floors, walls, and other purposes for which concrete is used.

3. In the preceding chapter, an attempt was made to ascertain the relative values of different kinds of aggregate. Table XVI., page 127, shews that the crushing strength of concrete, made with Portland stone and cement in the proportion of 10 to 1, is as great as that of pottery-concrete 8 to 1, and better than either ballast-concrete or flint-concrete 6 to 1. Granite-concrete 8 to 1 appears to be about equal to ballast-concrete 7 to 1.

The cleanliness, and variety of shape and size of the aggregate, and the proportion of voids in it, also affect the quantity that may be used. The importance of cleanliness has already been shewn, and the method of obtaining it by washing will be considered in the next chapter.

Voids in Aggregate.—The object usually aimed at in proportioning the ingredients of concrete is to obtain an aggregate containing the least possible quantity of voids or interstices, and to add to this sufficient mortar to fill these voids, with about 10 per cent. in addition to allow for the mortar joints and for imperfect mixing.

The method of ascertaining the voids in any aggregate is simple:—Fill a watertight box of known capacity with damp aggregate, shaking it well during the operation; then add sufficient water to fill it to the brim. The water must be poured from a vessel of known capacity, so that the quantity actually poured *into* the box may be ascertained. This quantity is the measure of the voids in the aggregate. The voids in sand can be ascertained in a similar way.

Another method is to weigh a certain quantity (say, 1 cubic foot) of the broken material and compare it with the weight of a similar quantity of the same material unbroken. The difference in weight divided by the weight of the solid stone, gives the proportion of voids in the

broken material; thus, if a cubic foot of solid granite weigh 168 lbs., and a cubic foot of crushed granite weigh 112 lbs., the difference in weight is 56 lbs.; divide this by 168, and we find the proportion of voids in the crushed granite to be one-third its bulk.

It will sometimes happen that the voids in the aggregate are so large that the filling of them entails either a very weak mortar or an extravagant amount of cement. In such cases, the aggregate is at fault, and the fault will as a rule be that the aggregate is of too uniform a size. The least quantity of voids will be found in those aggregates which contain pieces of various sizes, and machine-broken material usually fulfils this condition better than hand-broken.

It is impossible to state definitely what will be the voids in various aggregates, as so much depends on the shape and size of the pieces, and on the method of measurement. The following table shews that the voids in sandless aggregates may vary from 24 to 51 per cent. of the total volume, and these are probably not the extreme limits of variation.

The tests by Mr. Sandeman are of particular interest. They seem to shew (1) that flat oblong pieces tend to create greater voids than more cubical or rounded pieces, (2) that aggregates, consisting entirely of large stones, contain a large percentage of voids, (3) that large stones and flat oblong stones may be added to good aggregates consisting of stones of various smaller sizes, without detriment, (4) that good *gravel*, screened free from sand but containing pebbles and stones of all sizes up to 2½ inches, contains a very small percentage of voids, (5) that the least percentage of voids is found in aggregates containing stones of the most various sizes, from coarse sand upwards.

Tests Nos. 3 and 7 are very instructive. They shew that the coarse open aggregates 1 and 5, mixed with the fine compact aggregates 2 and 6, yield a mixture only slightly inferior to the latter.

The test No. 8 is one of a series given by Lieut.-Col. Gillmore in his book on "Limes, Hydraulic Cements and Mortars." He succeeded in obtaining aggregates with a

TABLE XVII.—PROPORTION OF VOIDS IN VARIOUS AGGREGATES.

No.	Nature of Material.	Size of Pieces.	Weight per cub. ft. in lbs.	Percentage of Voids.	Authority.
1	*Welsh Limestone*, crushed into irregular flat oblong pieces	To pass 3-inch ring when gauged narrowest way.	95	50·9	Sandeman.
2	*Gravel*, screened free from sand.	Small pebbles up to $2\frac{1}{2}$-inch ring.	111·5	33·6	"
3	Nos. 1 and 2 mixed in equal proportions.	Small pebbles to 3-inch ring	113·5	34	"
4	*Anglesea Limestone*, mason's shivers.	Small gravel up to 4-inch ring.	90·5	48	"
5	*Runcorn Red Sandstone*, broken by hand.	From 4 to 8-inch ring.	74	50	"
6	do.	From sand to 4-inch ring.	92	34	"
7	Nos. 5 and 6 mixed in equal proportions.	Sand to 8-inch ring.	91·5	36	"
8	Equal mixture of— a. *Limestone*, ... b. *Gravel*, screened free from sand.	 All sizes below 2-inch cubes. From size of pea to hen's egg.	...	24	Gillmore.
9	*Stone*	Up to $2\frac{1}{2}$-inch.	...	37	Rivington's "Notes."
10	"	" 2 "	...	39	"
11	"	" $1\frac{1}{2}$ "	...	42	"
12	*Shingle*	...	...	33	"
13	*Thames Ballast*, containing sand .	...	...	17	"

minimum percentage of voids. Ordinary limestone was crushed by a Blake's stone-breaker into pieces of all sizes below 2-in. cubes and of various shapes; and gravel

was obtained from the sea-shore, consisting, after the sand had been screened out, of pieces varying "from the size of a pea to that of a hen's egg." He found that the least amount of voids occurred in those mixtures which contained 15 measures of gravel and from 11 to 15 measures of broken stone. The worst mixture (15 to 27) contained only 30 per cent. of voids; the best (15 to 13) contained 23 per cent.

This is a vast improvement on the voids mentioned above for broken stone of nearly uniform size. *Solid* concrete made from the latter would be 20 to 30 per cent. weaker than that made from the former, while the cost of the two would be practically the same.

VOIDS IN SAND.—The voids in any sand vary largely according to the moisture it contains. Sand, slightly damp, may contain more voids than when dry, but very wet sand may contain less. Rounded grains induce smaller cavities than angular, and those in turn than flat. Different methods of measurement also disclose apparent discrepancies.

Sand consisting of grains of uniform size, contains 50 per cent. of voids,* and sand consisting of unequal grains may contain only 36 per cent. Roughly speaking, therefore, the percentage of voids in either sand or aggregate, varies from one-half to one-third the volume in each case.

MORTAR.—In calculating the amount of mortar required to fill the interstices in any aggregate, due allowance must be made not only for the voids in the sand itself, but also for the shrinkage in both the sand and the cement when these are mixed with water.

Roughly speaking, the bulk of Portland cement is, according to Mr. Sandeman, reduced 10 per cent., and of sand 20 per cent., by mixing with water, and the contraction in volume caused by mixing cement and sand together, is about 5 per cent. According to Mr. Sandeman, a

* See page 113, chapter x.

further contraction of 4 per cent. takes place during the setting of the mortar.* From these data, we may calculate that cement and sand (1 to 1) will produce mortar about 76 per cent. of their volume, (1 to 2) about 74 per cent., and (1 to 3) about 73 per cent.

Other experiments by different operators shew that these figures are only approximate; for instance, the shrinkage of Portland cement on being made into mortar is, by some, estimated to be not less than 15 per cent.

SOLID CONCRETE.—With ordinary aggregate consisting of fragments of various shapes and sizes, and containing about 33 per cent. of voids, the following mixtures will produce solid concrete :—

TABLE XVIII.—PROPORTION OF DRY INGREDIENTS (IN VOLUMES) TO PRODUCE SOLID CONCRETE.

Portland cement	1	1	1	1	1	1
Sand	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$
Broken material	3	4	5	6	7	8

But as we have already shown, solid concrete does not necessarily offer a greater resistance to tensile or transverse stress than does porous concrete; resistance to these stresses depends rather on the strength of the mortar, provided always that there is enough mortar to coat the whole surface of every fragment of aggregate, so that the pieces shall always have a film of mortar between them.

Where impervious concrete is required, it is necessary not only that the voids in the aggregate be completely filled by the mortar, but also that the voids in the sand be completely filled by the cement. To allow for imperfect mixing and for the coat of mortar between the fragments

* We have already seen that good Portland cement neither contracts nor expands to any ordinarily appreciable extent, during its setting and hardening. This further contraction of 4 per cent. ought perhaps to be considered due to the condensing effect of water on the mixture of sand and cement.

of the aggregate, an excess of mortar equal to at least 10 per cent. of the voids in the aggregate must be used, and to allow for the film of cement coating each grain of sand, an excess of cement equal to 10 per cent. of the voids of the sand must be used. The sand also may contain finer grains than would be the case if strength and not imperviousness were aimed at.

QUANTITY OF CONCRETE PRODUCED.—We have seen that sand and cement shrink in bulk on being made into mortar. In the same way, when cement, sand, and aggregate are mixed together, the bulk of concrete produced is less than the bulk of the several ingredients. The amount of shrinkage varies according to the voids in the materials, according to their wetness when measured, according to the proportion in which the materials are mixed, and according to the amount of ramming to which they are subjected.

If the aggregate contain little voids, and the sand and cement be about 10 per cent. in excess of these voids, the measure of the aggregate may be taken as the measure of the finished concrete. Frequently, however, the finished concrete measures even less than the aggregate, because the latter contains an amount of voids in excess of the mortar, and these voids are to a great extent eliminated by ramming. Where an excess of sand is used, the finished concrete will measure more than the aggregate.

No hard-and-fast rule can be laid down as to the amount of concrete which will be produced by different materials. Moist Thames ballast, when made into concrete with lime or cement, but without further admixture of sand, appears to shrink from 0 to 10 per cent. If the materials are dry when measured, the shrinkage may reach 15 or more per cent. The results of a careful test by Mr. Wm. Kidd are given in the *Proceedings of the Inst. C. E.*, for 1890–1 (part III.), and as they throw considerable light on the whole of the subject treated in this chapter, we reproduce it.

TABLE XIX.—COMPOSITION OF CONCRETE BLOCK.

Materials.	Measurement of dry material.		Interstices to be deducted.	Net solid material.	Per cent. of finished block.
	volumes.	cub. ins.	cub. ins.	cub. ins.	
Slag Cement	1	987·58	144·78*	842·80	26·9
Sand, coarse and containing small pea gravel	1	987·58	236·35	751·23	24·0
Gravel, to pass ¾-inch ring	½	493·79	160·37	333·42	10·7
Slag, to pass 4-inch ring, and be held by 1-inch ring...........	3	2962·74	1458·70	1504·04	48·0
Totals ...	5½	5431·69	2000·20	3431·49	109·6
Deduct settlement after mixing†				298·49	9·6
Net measurement of finished block.........				3133·00	100

The water used in mixing the ingredients measured 394·27 cub. ins.

The finished block measured less than 58 per cent. of the total dry ingredients measured separately, and nearly 10 per cent. less than the bulk of the gravel and slag measured separately. The gravel and slag, if measured together, would probably have been very nearly of the same bulk as the finished concrete.

Mr. Robert Pickwell, A.M.I.C.E., found that 1 cub. ft. Portland cement + 2·5 cub. ft. sand + 7·5 cub. ft. slag broken to pass a 2½-inch ring and including the dust formed in crushing, yielded 7·3 cub. ft. concrete, *i.e.* the finished concrete was practically equal in bulk to the broken slag. Mr. F. N. Thorowgood found that 1 cub. ft. Portland cement + 2·5 cub. ft. sand + 6·17 cub. ft. broken stone, yielded 6·94 cub. ft. concrete.

* Shrinkage after wetting, equivalent to 14·6 per cent.

† Presumably this represents the extent of the error in Mr. Kidd's calculations, as the "net solid material" is not of a compressible nature.

CHAPTER XIII.

THE MANUFACTURE OF CONCRETE.

Care and skill necessary—Breaking the aggregate—Size of aggregate—Washing the aggregate—Measuring the ingredients—Mixing, by hand and by machine,—*Portland Cement*, *Lias Lime*, *Selenitic Lime* — Concrete-Mixing Machines — Depositing — Packing—Ramming—Layers—Protection during setting.

Care and Skill Necessary.—We are sometimes told that one of the advantages of using concrete is that skilled labour is not required, but that anyone who can handle a spade can make it. This is only half the truth, and like all half-truths, it is dangerous: concrete-making can undoubtedly be carried out almost entirely by labourers, but —and it is an important reservation—there must be continual intelligent supervision. There is nothing which the architect has to use, which requires more careful superintendence than concrete, and perhaps this is one reason why it has come so slowly into use. Concrete of a sort may be easily made, but it is not easy to make really good concrete. Each ingredient must be tested or strictly examined, and further, every process in the manufacture must be closely watched. For, however good the ingredients may be, the resultant concrete may be little better than consolidated gravel or broken-stone, unless the measuring, mixing, depositing, ramming, and protection during setting, be carefully attended to.

Breaking the Aggregate.—For small quantities of concrete, stone and brick, &c., are usually broken by hand with ordinary stone-breakers' hammers, but when large quantities are required machines are preferable, as they

effect a saving of both time and money. This is especially the case, when the aggregate is very hard, as granite or syenite. Besides this, the stones broken by hand are too uniform in size to make the best concrete; experiments have shewn that machine-broken stones give better results.

There are several kinds of stone-breakers made now-a-days, from the hand-power machine which one man can work, to the powerful steam-driven machine which will turn out about ten tons of 2-inch cubes in an hour.

The most common kind of machine is of the "Blake" type, in which the stone is cracked between a jaw (moving backward and forward) and a fixed part of the machine. The original "Blake" patent has expired, and several modifications of it are now made by various manufacturers. Machines of this type exert a direct crushing stress on the stone, and produce less dust than machines which have a grinding action; as dust detracts from the strength of concrete, this feature of the jaw-crushers is an advantage.

Among the various machines of this type is the one illustrated by Figs. 4 and 5, known as the "Simplex Combined Stone-Breaker," and patented by Messrs. S. Mason & Co. of Leicester, in 1884. By changing the position of the driving-wheel, and by using different faces to the crushing jaws, the machine can be used for different kinds of work. When arranged, as shewn in Fig. 4, it has a direct cracking motion; in Fig. 5 it has a grinding motion. The former is useful for ordinary concrete; the latter is adapted for the production of smaller-sized aggregates, as for paving, &c., but as the pieces produced vary considerably in size, they ought to be passed through a screen on leaving the machine, so that the suitable pieces can be automatically separated from the remainder.

The machine, when arranged as shewn in Fig. 4, has the driving wheel attached to the lower shaft (marked 14). The middle portion of this shaft is eccentric, and consequently the revolution of the shaft causes a forward and backward motion of the "pitman" (6); the movable toggle (4) is bolted to the pitman, its projection (and

consequently the opening between the crushing jaws,) being altered as required by means of loose strips of iron, as shewn between the numerals (4) and (6). The nose of the toggle fits into a groove in the back of the jaw-stock (1), and communicates its forward and backward motion to the latter. If the nose of the toggle be inserted in the bottom groove, the movement of the jaw will be only small, and the machine will be in the best form for cracking hard stone. If the toggle be inserted in the uppermost groove, the motion will be nearly doubled, and

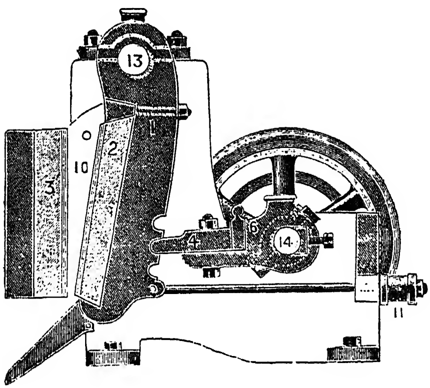


Fig. 4.—Simplex Combined Stone-Breaker, with Cracking Motion.

the machine will then be best adapted for breaking soft stone.

The jaw-stock swings on the upper eccentric shaft (13), and has a corrugated face (2) of chilled cast-iron secured to it. Opposite the face-jaw is a similar "fast" jaw (3), kept against the frame of the machine by a wedge-plate (10) at each side of the mouth. The jaw-stock is kept against the toggle by means of the spring (11).

When the machine is arranged as shewn in Fig. 5, the revolution of the upper eccentric shaft (13) causes an up-

and-down motion in the jaw-stock (1), while at the same time the toggle induces a slight forward and backward movement. The jaw-stock has therefore a rotary or grinding action. The jaws, it will be noticed, differ in section from those shewn in Fig. 4.

In both machines the lumps of stone are fed into the mouth above the numeral (10), and after being crushed, the pieces pass out of the shoot at the bottom. To this a

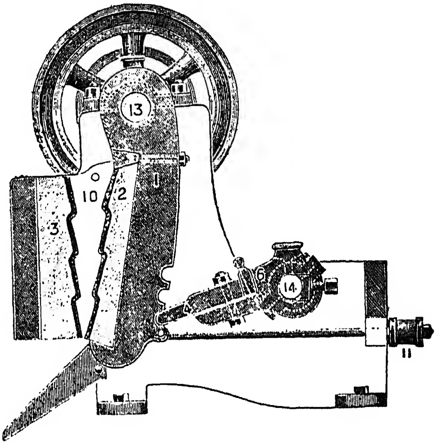


Fig. 5.—Simplex Combined Stone-Breaker, with Grinding Motion.

cylindrical screen, perforated with holes increasing in size from the machine to the outlet of the screen, can be attached, and the pieces, which are too large to be used in the concrete, can be returned to the machine by means of elevators or otherwise, or can be reduced by passing them through a roller mill.

Another kind of stone-breaking machine is of the "coffee-mill" type. Machines of this class consist of a hollow corrugated cylinder, (or cone with base upwards,) in which a solid corrugated cone is placed base downwards,

the base of the cone being slightly less than the internal diameter of the cylinder. A vertical shaft passes through the centre of the cone, and works in bearings at the top of the machine. The bottom of the shaft rests in a hole slightly out of the centre of a heavy horizontal wheel, which is made to revolve by means of bevelled cogs or otherwise. The revolution of this wheel induces an oscillating motion in the cone on account of the eccentricity of the bearing of the latter. The stone is broken between the cone and the cylinder by the oscillation of the former.

Machines of this type will do nearly twice as much work as those of the "Blake" type, but, although they are sometimes used for the hardest stone (as for syenite at Croft), they are better adapted for softer material. The crushing faces of these machines cost much more in renewals than those of the jaw stone-breakers.

A third class of machine is the "roller" mill. In this machine two chilled cast-iron rollers, with teeth set chequerwise, are made to revolve in opposite directions by means of cog-wheels. The teeth in the rollers are of different sizes and distances, according to the size of the broken stone required.

Such machines are not adapted for breaking up large lumps of stone, but are usually employed in conjunction with a jaw stone-breaker to reduce the larger pieces which have passed the latter. No stones can pass through a roller mill larger than the size to which the roller-teeth are set. Rollers can be had for crushing stone into various sizes, from 3 inches down to $\frac{1}{4}$ in. or even less.

Size of Aggregate.—The smaller the several pieces of the aggregate are, the smoother will be the surface of the finished concrete, but a small aggregate gives weaker concrete than a large one, with the same amount of cement.

The size of the largest pieces varies in different specifications and for different purposes. For concrete in large masses, as in breakwaters, dock-walls, &c., it is best to have an aggregate ranging up to a considerable size, the

largest pieces being such as will just pass through a 3, $3\frac{1}{2}$, or even 4-in. ring.

The same reasoning we employed to explain the advantages of coarse sand over fine sand, p. 111, applies to the aggregate; the greater the number of pieces in a given quantity of aggregate the larger is the extent of surface to which the mortar has to adhere, and consequently the greater must be the excess of the mortar over the voids. But there is a limit of size which it is not advisable to exceed. This limit was fixed by the Metropolitan Board of Works in 1872 at 2 in. for all concrete in buildings, but there is no doubt that, for foundations and walls more than 12 in thick, an aggregate containing some larger pieces would prove, strength for strength, more economical. Pieces too large have a tendency to wedge together and to leave cavities in the concrete; they should be laid separately by hand as packing in the different layers.

It is not often that the size of the largest pieces of the aggregate is allowed to exceed 4 in., even for concrete in large masses, as in breakwaters. For the foundations and walls of buildings, and for retaining walls, the limit of size may be placed at 3 in., or one-sixth the thickness of the foundation or wall, if this be less than 18 in. and more than 7 in. In London, of course, the maximum limit is fixed at 2 in. for all concrete in buildings. For walls and floors less than 7 in. thick, the limit of size may be placed at one-fifth the thickness of the concrete. For the surface coats of paving, the aggregate is usually broken into $\frac{1}{2}$ in. or $\frac{3}{8}$ in. cubes.

A word of warning may here be uttered anent the apparent size of broken stones. To the unpractised eye, they always look smaller than they really are, and there is great difficulty in getting labourers to break the stones small enough. An aggregate specified to pass a 2-in. ring will be found, if broken by hand, to consist largely of pieces which would barely pass a 3-in. ring, and to contain many even larger fragments. This aggregate is in many cases tacitly accepted by the architect or clerk-of-works

without being submitted to any test whatever. It is such a simple matter to pass the broken stone through a sieve or screen, that architects should specify it to be done. Need it be said, that a good clause in a specification ought to be strictly enforced?

WASHING THE AGGREGATE, &c.—We have already pointed out the dangers which may arise from the use of dirty sand and aggregates, and have stated that these can be obviated by thoroughly washing them.

The washing of the aggregate can most conveniently be done immediately before mixing the concrete, and can be carried out on the same platform, although it is better to have separate platforms, as the slope, which is required in the washing-platform, may cause cement to be carried away if the platform be used for mixing purposes. The washing-platform may be of boards or planks, and must be laid with sufficient inclination, so that the dirt can be easily removed by the water. The material should be shovelled backward and forward by one or more men, an ample supply of water being at the same time poured upon the heap by another man. Thorough agitation of the aggregate and a plentiful amount of water are needed, and the operation should be continued until the effluent water shows little trace of impurity.

The washing of the aggregate leaves it in a damp state, and, therefore, in the best condition for making strong concrete. Where washing is not adopted, the aggregate ought to be sprinkled with water before using, as a dry aggregate absorbs moisture from the cement, and leaves it without sufficient water for its proper induration.

Pit-sand and sand from sluggish streams are also improved by washing, as they contain earthy matters, clay, and mud. The washing cannot be carried out conveniently on an open platform, as the water would carry away a great part of the sand. Sand-washing machines, for hand or steam-power, can be obtained, and are economical where large quantities of impure sand have to be dealt with. Where this is not the case, the sand may be placed in a tub

or trough, into which a stream of water is turned; the sand must be well stirred, and the fine impurities will be carried away by the overflowing water.

A great part of the salt contained in sea-sand may be eliminated by washing. Mr. E. C. Morgan recommends the following method. Fill a tub with the sand, and into the sand push a small iron pipe long enough to reach to the bottom of the tub and connected at the other end by an india-rubber pipe to the water-main; the water rises through the sand and flows over the edge of the tub, gradually carrying the salt with it. "The sand should be washed as soon as it is taken from the beach."*

The washing would be more rapid and effectual, if the sand were agitated during the process.

MEASURING.—The various ingredients must be carefully measured in boxes separately. For rough work, carried out by the owner's workmen, the aggregate may sometimes be measured with sufficient accuracy in wheel-barrows, a certain number to each bag of cement. But for all concrete which may be subjected to considerable stress, and for all contract work, each ingredient must be measured in a box. On no account must any deviation from this rule be allowed, for without accurate measurement the concrete cannot be of uniform strength—some portions will have too much cement and some too little, and the latter will be the measure of the strength of the concrete. And in addition to this lack of uniformity, it is quite possible that the proportion of cement used will be less than that specified, and in this case the whole mass suffers.

The quantity of concrete which can conveniently be mixed by hand at one time does not exceed one cubic yard, but it is better to mix less than this, especially if the concrete be fine (as for thin walls, floors, &c.) or the cement be quick-setting. Having decided upon the amount of aggregate to be measured, it is easy to calculate the size of the boxes required for that and for the other ingredients.

* Gwilt's "Encyclopædia of Architecture."

There are severals methods of measuring the ingredients. Sometimes a bottomless box or frame is used for the aggregate, with two handles on opposite sides, and, preferably, with the sides sloping inwards to facilitate the lifting of the frame when filled, as shown in Fig. 6. This is laid on the mixing board and filled level with the top; upon it then is placed another frame of the same length and breadth but of smaller depth,—varying according to the specified ratio between cement and aggregate,—and this is then filled with cement and struck level with a straight-edge.

The best method, is to fill the aggregate into a measuring-frame as above, then place on it another of suitable depth

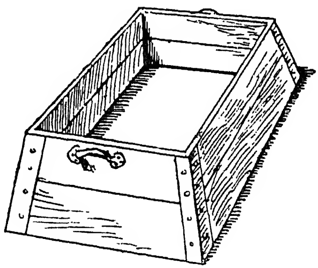


Fig. 6.—Measuring-Box.

and fill it with sand; lift the two frames by the handles in their ends, and the sand is spread over the aggregate; the cement must be measured in a box (with a bottom) and emptied over the heap. For instance, in the case of concrete specified to be composed of 1 part cement, 2 parts sand, and 4 parts broken stone, the stone could conveniently be measured in a frame 4 ft. by 2 ft. 6 in., by 2 ft. deep, the sand in a similar frame 1 ft. deep (or preferably in one rather deeper, say 3 ft. by 2 ft. 6 in., by 1 ft. 4 in. deep), and the cement in a proper box 2 ft. by 2 ft., by 1 ft. 3 in. When large shallow boxes or frames are used, there is more liability of inaccurate measurement.

In exposed situations, the mixing should be done under cover, so that the cement may not be carried away by the wind.

MIXING.—There are two ways of mixing concrete, the "dry" and the "wet." In the former all the ingredients are mixed together before any water is added; this is the method usually adopted in England. The wet method is common in France; and consists in the cement or lime, and the sand, being made into mortar and then added to the broken material. The name *béton* has been applied to concrete made in the French way. For cement-concrete the English method is the better, for lime-concrete the French has some advantages.

Concrete can be mixed either by hand or by machinery, the latter for large quantities being considerably more economical. Mr. Bernays, in 1880, recommended the mixing of concrete by hand, for the reason that machines cannot be fixed as near the place of deposition or moved as easily as simple wood platforms can; at the same time he acknowledged that some machines did their work perfectly. Since that time, however, machines have come more and more into use, many being mounted on wheels, so that Mr. Bernays's objection loses most of its weight. Nowadays many machines are employed by building-contractors, although they are not, of course, as large and powerful as those used in harbour-works. For small quantities of concrete, mixing by hand is almost invariably adopted. Experiments seem to show that concrete mixed in a good machine is stronger than hand-made concrete (See Page 164.)

Hand-mixing requires considerable care. The points to be aimed at in "dry" mixing are the following:—The platform should be as near the place of deposition as possible; the sand and the broken material or gravel must be turned over so that the voids in the latter are filled by the former; the cement must be distributed equally throughout the whole; sufficient water must be added so that it may cause the cement to form a thin film around every particle of sand and fragment of larger material, but

not enough to wash away the cement; with quick-setting cement the operations must be rapidly completed.

Fresh cement will take up more water than stale cement. A smaller quantity of water can be used in concrete if this be well rammed.

Gillmore is right when he says that concrete, "when ready for use, should appear quite incoherent, containing water, however, in such quantities that a thorough and hard ramming will produce a thin film of free water upon the surface under the rammer without causing in the mass a gelatinous or quicksand motion."

Portland Cement.—For Portland-cement concrete, Mr. Grant recommends that the ingredients be turned over at least three times dry, the water then added, and the whole mass turned over three or four times wet. It is not often, however, that so much manipulation is specified; more commonly it is specified that the materials shall be turned over twice dry and twice wet, and this is sufficient.

Sometimes the operation is performed entirely with spades, either two or preferably more men being employed, and the heap being thoroughly turned over by them in shovelling it from one part of the mixing-platform to another, and back again; the materials have thus been turned twice dry. Water in proper proportion is then sprinkled upon the heap by another man through a rose; if the water be poured from pails, it is probable than some of the cement will be washed away and that excess of water will be used. The materials are again turned over during the operation of sprinkling, and after a fourth turning the concrete should be ready for use.

In addition to the two or more men with spades, another man with a large two-pronged rake is frequently employed to rake the ingredients to and fro as they are turned by the spades: this is an improvement on the other method.

Sometimes the lime or cement, and sand, are first carefully mixed and afterwards the broken stone is added, the whole mixture is then well turned over before the water is added, and again afterwards.

Lias Lime.—This method has much to recommend it, and is indeed specifically enjoined by several makers of hydraulic lime. The following is a copy of the "Instructions to Foremen, Workmen, and others" issued by the Barnstone Blue Lias Lime Co. :—

"1. Provide a clean floor to make concrete from *ground* lime. Measure *one* part lime and *one* part clean sand or ashes; mix in a dry state. Measure the right quantity of broken stone, slag, brick-ends, or ballast; use in the following proportions :—3 or 4 parts stone or ballast to 1 part lime and one part sand. Spread out the stones or ballast in a thin layer; throw the dry mixture of lime and sand or ashes over the rough material; then sprinkle the whole with a sufficient quantity of water to make the mixture work, and turn it over sharply until every particle of the rough material is coated. It should then be quickly thrown into a bed and well rammed.

"2. Three men should not attempt to work more than half a bag of lime at once. To ensure good results it is of great importance that the mixture should not commence to set before it is put into the work.

"3. In cases where our lime is used below water, the water should be kept off for 24 hours or, when practicable, longer, after which time it may, at the contractor's option, be let in; it will assist in hardening the concrete or mortar.

"4. Great care should be taken that the sand and ashes used are entirely free from loam or dirt."

The last clause but one is worded in a most mysterious manner. The first clause, it will be noticed, does not insist on the whole of the ingredients being turned over dry; the necessity for this is not so great seeing that the sand and lime have been well mixed dry, but it would certainly be of advantage.

Selenitic Lime.—Selenitic lime requires different treatment from any other lime or cement, the difference consisting in mixing it with water "to the consistency of creamy paste" before it is brought into contact with either

sand or aggregate. If a mortar-mill is available, the following method is recommended by the Selenitic Cement Co. :—

1*st.*—"Pour into the pan of the edge-runner 4 full-sized pails of *water*" [about 12 gallons].

2*nd.*—"Gradually add to the water in the pan 2 bushels of *Selenitic Lime*, and grind to the consistency of creamy paste."

3*rd.*—"Throw into the pan 2 bushels of *clean sharp sand*, burnt clay, ballast, or broken bricks, which must be well ground until thoroughly incorporated. If necessary, water can be added to this in grinding, which is preferable to adding an excess of water to the prepared lime before adding the sand."

4*th.*—"Spread 12 or 14 bushels of broken stone or other material upon the mixing platform; cover these with the mortar prepared in the mill; and turn the whole two or three times to ensure thorough mixing."

If, however, a mortar-mill is not available, "an ordinary tub (containing about 30 or 40 gallons) or trough with outlet or sluice may be substituted." The *modus operandi* will be somewhat different.

1*st.*—"Pour into the tub 4 full-sized pails of water."

2*nd.*—"Gradually add to the water 2 bushels of Selenitic lime, which must be well stirred until thoroughly mixed with the water to the consistency of creamy paste."

3*rd.*—"Measure on the mixing platform 2 bushels of sand, and 12 or 14 bushels of broken stone or other material, and mix these *dry*."

4*th.*—"Pour the lime-paste upon the aggregate and turn the whole over two or three times."

Concrete, made according to the foregoing instructions, will consist of *one* part lime, *one* part sand, and *six* or *seven* parts broken material, and will be suitable for ordinary foundations. A cubical box, measuring (inside) $13\frac{1}{8}$ inches on each side, contains about 1 bushel.

It is said that an addition to selenitic lime of one-sixth its bulk of Portland-cement quickens the setting.

Béton.—In the French method of mixing *béton*, the lime or cement and sand are first made into mortar, and this is then mixed with the broken stones, &c. When lump or shell lime is employed, this system is the best, as the lime can be thoroughly slaked, and then ground in a mortar mill, thus eliminating the danger of blowing which may result from the hydration of coarse particles of lime after the fine portion has set. The mortar may be mixed in the proportion of 1 part lime or cement to 1½ or 2 parts sand.

Lieutenant Wright thus describes the operation of making *béton* at Boston (U.S.A.) :—" The concrete was prepared by first spreading out the gravel on a platform of rough boards, in a layer from 8 in. to 12 in. thick, the smaller pebbles at the bottom and the larger on the top, and afterwards spreading the mortar over it as uniformly as possible. The materials were then mixed by four men, two with shovels and two with hoes, the former facing each other, and always working from the outside of the heap to the centre, then stepping back and recommencing in the same way, and thus continuing the operation until the whole mass was turned. The men with hoes worked each in conjunction with a shoveller, and were required to *rub well into the mortar* each shovelful as it was turned and spread, or rather scattered, on the platform by a jerking motion. The heap was turned over a second time in the same manner, but in the opposite direction, and the ingredients were thus thoroughly incorporated, the surface of every pebble being well covered with mortar. *Two* turnings usually sufficed to make the mixture complete, and the resulting mass of concrete was then ready for transportation to the foundation. The success of the operation, however, depends entirely upon the proper management of the hoe and shovel, and though this may be easily learned by the labourer, yet he seldom acquires it without the *particular attention of the overseer.*"

Concrete-mixing Machines.—Several kinds of concrete-mixing machines have been invented. Some of these are made in sizes small enough to be worked by hand, but the

most usual method is to drive them by steam-power. Many concrete-mixing machines are used to-day for making the concrete required in the foundations and floors of large buildings, and they will doubtless come more into use when their advantages are more widely known. Machine-made concrete is more thoroughly and rapidly mixed than hand-made, and for considerable quantities it is much cheaper. Besides this, machines do their work with more uniformity than labourers, and constant supervision is not therefore as necessary. Probably before many years are over, architects will specify that all concrete in large works shall be mixed by machinery. Care will, however, have to be exercised by architects in approving concrete-machines, as many of these seem designed rather to turn out a large quantity of concrete than to insure the thorough mixing of the materials.

One of the first machines to be adopted was a simple revolving cylinder, inclined at an angle of 6 or 8 degrees to insure the forward movement of the concrete-materials. It was much used in Germany about thirty years ago, and is the germ from which many modern machines have sprung. The chief advantage of this type of machine is that it is continuous in action; the measured materials, after being turned over dry on the mixing platform, can be continuously fed into the cylinder at one end, and without cessation they are mixed with water and ejected at the other end. But this very advantage may prove to be a disadvantage if the cylinder be inclined too much; for in this case, the materials would pass out of the machine before they had been thoroughly mixed. No hard-and-fast rule respecting the inclination of the cylinder can be laid down, as it must vary according to the character of the concrete. A very small aggregate requires a greater inclination than a coarse one; an aggregate containing a large proportion of sand also requires a greater inclination than one containing little or no sand.

It was soon found that the plain inclined cylinder did not mix the materials properly, and an improvement was at length effected by riveting three or four dividing-plates to

the inside of the cylinder. These turned the materials over more thoroughly. *Le Mesurier's Concrete Machine* is, we believe, the earliest example of this improvement.

At first, the dividing-plates were fixed in a straight line from end to end of the cylinder, but they are now frequently arranged in a spiral form, each plate making about half-a-turn in the length of the cylinder. This arrangement facilitates the ejection of the concrete, and allows the cylinder to be retained at a moderate inclination.

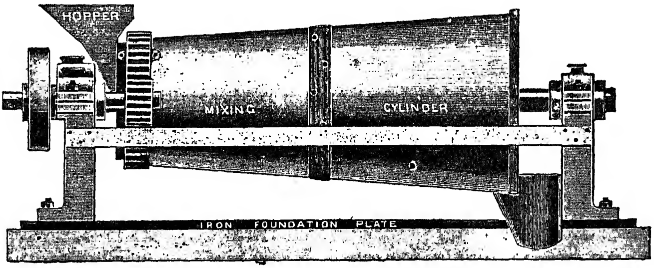


Fig. 7.—Messrs. S. Mason & Co.'s Concrete-Mixer.

A further modification of this type of machine is shown in Fig. 7, which represents a kind of concrete-mixer made by Messrs. S. Mason & Co., of Leicester. It will be seen that, in this machine, the mixing vessel, which is of steel-plate, is really not a cylinder, but the frustum of a cone. The change of shape is designed to assist the passage of the materials, and is of advantage especially for small aggregates. Three or four dividing-plates of 3 in. × 3 in. angle-iron, are riveted to the inside of the cone, and run straight from end to end. The different parts of the machine will be understood without further description. Hand-power machines of this kind may be had with cones 6 ft. long and 2 ft. in diameter at the smaller end, and steam-power machines with cones from 6 to 9 ft. long and 2 ft. or 2 ft. 6 ins. in diameter.

Waller's machine is on the same principle as the inclined

cylinder-machines already described, but instead of a cylinder with dividing-plates, he uses a mixing-vessel or tube, the cross-section of which may be described as a quatrefoil or, perhaps more accurately, as a Greek cross with all the angles rounded. As the tube revolves, the materials are turned from arm to arm of the cross, and well mixed together.

"*Ridley's Concrete-Mixer* has a *fixed* inclined cylinder with a central shaft carrying longitudinal shelves, which lift the materials as the shaft revolves, and mix them together." * This has no advantages over the simpler machines already described.

Stoney's Concrete-Mixer is an inclined open iron trough, along which the materials are forced by means of a revolving shaft carrying blades arranged in the form of a screw.

The second-class of concrete-mixers includes all machines, by which the mixing is effected within a closed revolving vessel. In these the action is not continuous, as in the foregoing class of machines, but intermittent. The requisite quantity of materials is put into the vessel, which is then closed and made to revolve a certain number of times, the proper number being ascertained by actual experiment for different mixtures. After the necessary revolutions have been made, the vessel is opened and emptied.

A simple machine of this kind was used in constructing the fortifications on Staten Island, New York Harbour, in 1870–1, and is described by Gillmore in his work on "Limes, Hydraulic Cements and Mortars." It consisted of a cubical wooden box, made to revolve by means of a shaft, which ran diagonally through the box from opposite corners. The box measured 4 ft. each way, and was charged with about 36 cubic feet of mortar and aggregate, measured separately. "Eight revolutions of the box," says Gillmore, "made in less than one minute, are found to be quite sufficient to produce the most thorough incorporation of the mortar with the broken stone and gravel."

* Rivington's "Notes on Building Construction," part iii.

Instead of a cubical wooden box, *Sykes's* machine has a short iron cylinder with a door at each end, and inclined in such a manner that a horizontal shaft passes through the upper part of one end of the cylinder and the lower part of the other. The eccentric position of the shaft causes the cylinder to revolve in a peculiar manner, the materials being tumbled about in various directions and so mixed.

Messent's Patent Concrete-Mixer consists of a closed box or chamber of a peculiarly irregular shape, made to revolve on an axle. Messrs. Stothert & Pitt, the makers, say that, "in from six to twelve revolutions (the number necessarily being varied according to the weight and nature of the materials), a more perfect mixture is effected than can possibly be produced by hand."

A simple apparatus, described by Gillmore, consists of a vertical shoot divided into several compartments by shelves or flaps hinged alternately on opposite sides of the shoot; the materials are placed in the uppermost compartment, and the flaps are then dropped to an angle of about 45 degrees by means of levers, so that the materials fall from one flap to another until they reach the bottom in a state ready for deposition. This apparatus does not appear to be used in England, and probably in America it has been superseded by machines of the kinds already described.

Depositing.—The mixing ought always to be done as near as possible to the place where the concrete has to be used. It is better to move the platform or machine when these would be more than about thirty yards from the point of deposition.

For foundations in shallow trenches the concrete can be thrown by spade straight from the platforms, if these are near the trenches, or can be wheeled in barrows and tipped. The method formerly advocated of tipping concrete from a height of three or four yards is now discountenanced, for the reason that the larger stones in falling become separated from the mortar and smaller stones, and the concrete is not therefore homogeneous and uniform. For the same reason,

shoots are now falling into disuse; a shoot has also the further disadvantage that the larger stones, on account of the velocity which they attain in passing down the shoot, fall some distance in front of its mouth; whereas the mortar, sliding gently down, drops vertically from the mouth, thus counteracting to a great extent the labour bestowed in carefully mixing the ingredients. This evil can be mitigated by turning over and re-mixing the concrete immediately it reaches the bottom of the shoot, but no time must be lost either in the original mixing or in the depositing if this second mixing is to do any good.

For deep trenches, the concrete, if it cannot be mixed in the trench, may be lowered in barrows or pails; sometimes it is carried down in hand-barrows; more frequently, however, it is tipped from the surface, as the cost of lowering it is not thought to be counterbalanced by the advantages gained.

For walls, floors, &c., it can best be carried and hoisted in pails or barrows.

The concrete ought to be deposited as soon after mixing as possible, as any disturbance of the mass, after the cement has begun to set, detracts from the ultimate strength. Rapidity of execution where quick-setting cement is used, is a point which must be carefully attended to.

For depositing concrete under water, hoppers or shoots are sometimes used; but it is better to use a box or skip, so arranged that its contents can be released when it touches the bottom, either automatically or by pulling a cord. Into the details of such work and of the bag system it is not our province to enter. We may just say that concrete, deposited in water, ought to be somewhat richer in cement than ordinary concrete, and that all motion of the water ought to be prevented if possible as it tends to wash away the cement.

Packing.—Considerable saving can be effected by packing rough stones into concrete, while it is being deposited. This can only be done of course when the concrete is in large

masses, as in foundations, retaining walls, harbour-works, and the like. Sometimes the "packing" amounts to as much as 25 per cent. or more of the total bulk of the work.

In heavy engineering works, some of the stones thus inserted contain a cubic foot or more, but in buildings smaller pieces must be used according to the thickness of the wall or foundation. Care must be taken that none of these lumps of stone are placed within 3 inches or 4 inches of the face of the wall or of each other, and the concrete should contain a proportionate excess of mortar in order that the packing may be properly united with the rest of the mass. All packing-stones should be wetted before being laid in the work.

It must be remembered that the difficulties of superintendence are much increased when packing is specified, as there can be little check on the quantity of packing which a contractor can put into a wall. For this reason it is better, in contract work, where the constant supervision of a clerk of works is not available, to forbid all packing and to use a well-broken aggregate, irregular in shape and size, and containing, therefore, as small a quantity of voids as possible. In this way, the cement will bind a larger quantity of aggregate, and the cost entailed by forbidding packing will be, to some extent, reduced.

Ramming.—The advantage of suitable ramming or punning is obvious. It compresses the concrete, rendering it more solid and free from voids, and squeezes out all superfluous water. We have seen that the Romans probably adopted it. Too much ramming, however, is dangerous, as it may be continued until the cement has begun to set, and in this case a loss of strength is entailed. For this reason, concrete made with Roman or other quick-setting cement ought not to be rammed at all.

Mr. E. C. Clarke (1885) "doubts the expediency of punning concrete, except when used in thin layers, as in pavement work, where it promotes consolidation and adhesion. In other cases, unless the concrete is very stiff,

punning tends to separate the more fluid portions and to produce strata of different density, and also disturbs the setting." Note the saving clause—"unless the concrete is very stiff."

Mr. Grant, however, carried out a series of experiments which showed conclusively that compression increases the strength of concrete. He declares that "for blocks, thin walls, sewers, arches, floors or paving, concrete may be punned in layers with advantage." The manufacturers of artificial stone and paving, and of concrete drain-pipes, almost invariably compress the raw material in one way or another in order that the goods may be strong and impervious to water.

The results of Mr. Grant's experiments on the crushing strength of concrete compressed and not compressed were given in Table XVI., p. 127. The compression was effected by beating the concrete into the moulds with a small mallet. The resultant gain in strength averaged 28 per cent. for the 1 to 6 mixtures, 28 per cent. for the 1 to 8, and 24 per cent. for the 1 to 10, a gain by no means to be despised.

But concrete not only gains strength by compression; its density, and consequently its imperviousness to water and its durability, are also increased. Without ramming it is impossible to have impervious concrete.

Of course the concrete of ordinary walls cannot be rammed with the same vigour with which the concrete of foundations may be rammed. For the latter a moderately heavy punner of iron, or of hard wood bound with iron, may be used, but such an implement, if used for walls, would most likely cause the wooden boards enclosing the wall to bulge out, and the appearance of the wall would be irretrievably spoilt. For walls, therefore, a lighter implement should be used. Concrete floors are frequently consolidated by beating with the back of the spade used in spreading the concrete.

Layers.—Opinions differ as to the thickness of the layers in which concrete should be deposited. Some advocate

thick layers, some thin ones. The lime-concrete foundations of the army headquarters at Simla were rammed in 3 in. layers. Layers so thin are very seldom adopted, because, whatever care may be taken, the joints between the layers are always a source of weakness. During the operation of punning, some of the water in the concrete is forced to the surface, and brings with it part of the constituents of the cement, causing sometimes a film of soft clayey matter upon the surface. This effectually prevents the adhesion of the next layer.

For this reason, concrete, which has been exposed for a day or two, should be swept clear of this matter, and also of all loose stones and dust, before another layer is added. The surface should also be well watered, and if good work is required, should be roughed with a pick, although this last operation is not as beneficial as is sometimes imagined. Mr. Bernays recommends that the surface of concrete in large walls, if it have been long exposed, should, in addition to being swept and watered, be dusted over with neat cement, and sometimes have a chase, say, 12 in. by 9 in., cut in it to form a key for the next layer.

Some persons think each layer, after being swept, ought to be watered with thin grout before the next layer is laid, but grout is somewhat uncertain in its action.

Layers 9 in. or 12 in. thick are often specified, but layers 18 in. thick are on the whole more satisfactory. Sometimes a thickness of 2 ft. or even 3 ft. is laid at one operation. Thick layers ought not to be attempted unless a good machine or a very large number of men are employed in mixing the concrete, as otherwise the depositing and ramming such a thickness may take so long that the lowest portion may have begun to set before the men can finish the upper part, and this will cause a disturbance of the setting, and consequent weakness. On the whole, it may be considered best to deposit concrete foundations less than 18 in. thick in one layer, and above this thickness in two or more layers not exceeding 18 in. each. The concrete of retaining walls may be rammed in 18 in. or 24 in. layers.

The frames used in forming the walls of buildings usually allow a thickness of 18 in. to be deposited at one operation, and never more than 24 in. Paving and floors must always be rammed in one thickness; the surface, however, may be finished with finer concrete after the mass has set.

In the formation of concrete arches, care must be taken that the concrete is not deposited in thin layers following the curve of the arch, but the full thickness of the concrete must be laid at once, and rammed in the direction of the thrust, so as to form longitudinal courses like continuous voussoirs, having the joints between adjacent courses radial to the curve of the arch. This is an important point, especially if the whole arch cannot be completed in one day. The breadth of the longitudinal courses will depend on their depth, &c.; it may be from 6 in. to 18 in. for large arches. Small arches, such as are used in floors, will be laid at one operation. During the ramming of the concrete in large arches, a movable board with curved face can be used to retain the concrete and to form the extrados.

PROTECTION DURING SETTING.—It is useless to make good concrete, unless care is taken to protect it until it is hard enough to take care of itself.

Any disturbance of concrete during setting injures it. Cement cannot be gauged, left to set for a short time, and worked up again without loss of strength. Cement ground with water in a mortar-mill for half an hour makes considerably weaker briquettes than cement gauged by hand as quickly as possible. After cement has begun to set, it ought not to be disturbed until it has hardened sufficiently to bear easily any weight that may be put upon it. Walking across a concrete floor, before the hardening is sufficiently advanced, will cause rotten places in the concrete. For this reason, all concrete, especially in floors, arches, and roofs, should be carefully protected after being laid; all traffic across such concrete being absolutely forbidden for as long a period as possible.

The duration of the protection will vary according to the kind of cement employed, and according to the richness of

the concrete. Quick-setting cements, such as Roman cement and plaster of Paris, do not require as long a protection as Portland cement. In the case of floors, where the concrete is the weight-carrying material, the centres should not be struck in less than 4 or 5 weeks, if Portland cement is the matrix; whereas with plaster of Paris one week would suffice. Again, sand retards the setting and hardening of cement—see Fig. 3, p. 74—and therefore concrete containing a large proportion of sand requires longer protection than concrete containing little or no sand. When traffic across concrete is permitted before it has hardened sufficiently, it may be protected by covering it with moist sand or sawdust or sacks, on the top of which strong planks are carefully laid where required. The precautions to be taken to prevent injury being done to concrete by heat and cold, &c. will be considered in the next chapter.

Strength of Hand-mixed and Machine-mixed Concrete.—The following record of tests by Mr. E. L. Ransome shows that machine-mixed concrete may be considerably stronger than concrete mixed "skilfully and thoroughly" by hand. The tests were made in America on 4 in. cubes, but in the table the ultimate loads are given in English tons per sq. ft.

Table XIX., A.—Compressive Strength of Hand-mixed and Machine-mixed Concrete.

Age in weeks	1	2	3	4
A. 1 *cement to* 12 *limestone.*	Tons per square foot.			
No. 1. Mixed by hand	16	22·3	22·3	22·3
„ 2. „ in mill and turned 56 times	32·1	32·1	32·1	38·4
„ 3. „ „ „ 343 „	44·6	39·2	49·1	40·1
B. 1 *cement to* 6 *fine granite.*				
No. 1. Mixed by hand	56·2	72·3	67·8	80·3
„ 2. „ in mill and turned 300 times	72·3	88·4	96·4	88·4

CHAPTER XIV.

THE WEATHER—ITS EFFECTS ON CONCRETE.

General Effect—Heat, moist and dry—Variation of Temperature—Frost, Effect on Briquettes, and on Concrete—Remedies :—I. 1, raising temperature of materials ; 2, lowering freezing-point of water (Salt, Soda, Sugar, &c.) : II. 1, lowering freezing-point of water ; 2, hastening setting, &c. ; 3, warming surrounding air—Expansion and Contraction.

General effect of Heat and Cold.—Concrete requires protection not only against traffic, but also against extremes of temperature, as the state of the atmosphere has a very great influence on the hardening of hydraulic limes and cements. The scorching heat of summer is almost as injurious as the biting cold of winter. The former is dangerous, because it abstracts the water which is necessary for the proper crystallisation of the lime ; the latter, because it freezes the water, causing it, therefore, to swell and crack the mortar, so that sometimes the latter becomes little better than so much sand.

Heat, Moist and Dry.—Moist heat hastens the setting of cement, and also its hardening ; it is dry heat which is injurious. Pats of Portland cement, which set properly and attain considerable hardness in a few hours, will, if kept on a mantel-piece over a good fire for a few days, become quite easily friable. And yet it is not very many years since a correspondent in *The Engineer* advocated the lighting of fires every evening at the feet of mill chimneys, in order to set the mortar which had been laid that day. Heat will *dry* mortar, but that is a very different thing from causing it to *set*. Rapid drying is injurious.

The rapid drying of floors and roofs may be prevented by covering the concrete for a week or more with a shallow pool of water renewed when necessary, or with a layer of sawdust or sand kept continually moist, or with straw, sacks, &c., which protect the concrete from the direct action of the sun and wind.

Portland-cement stucco is seldom sound when executed in hot summer weather, unless great care has been taken in wetting the concrete or brickwork before applying the stucco; protecting the wall as far as possible from the direct action of the sun is also a useful precaution. Warm, damp weather is most suitable for the setting of cement, whether in stucco or concrete, but damp weather, even somewhat cold, is better than extremes either of heat or frost.

Variation of Temperature.—Variation of temperature is also to be avoided as much as possible. Mr. W. W. Mackay of the Docks Department, New York, found in 1876 that Portland-cement briquettes, made and kept in water, at a uniform temperature of 60° Fahr., were, at the end of 7 days, 30 per cent. stronger than exactly similar briquettes which were made at a temperature of 60° to 70° and kept in water varying daily from 70° down to about 40°. If this short range of temperature retards the hardening of neat cement to such an extent, we can understand that the effect will be greater with greater cold acting on mortar and concrete.

It frequently happens that concrete is exposed to the heat of the sun by day and to keen frost by night, and this is almost sure to cause cracks in the work. Covering the concrete with straw, sacks, &c. will afford some protection, but in many cases it will be best to stop the work until the weather is more suitable.

Frost.—Almost every architect and builder learns by bitter experience the ill effects of frost on newly-made mortar and concrete. Its primary effect is to crystallise the water in the mixture, and this crystallisation has two results,—it prevents the chemical union of the water with the cement, and, as water expands in solidifying, it forces

apart the different constituents of the mortar and concrete, so that, when a thaw occurs, there is little or no coherence between them. Undoubtedly in many cases mortar and concrete harden after having been attacked by frost, but it is equally true that they never attain the strength of similar but unfrozen mixtures.

EFFECT OF FROST ON BRIQUETTES.—Laboratory experiments seem to show that frost does little harm to Portland-cement briquettes. A series of tests by Herr Böhme led him to the conclusion that the effect of frost was merely "to retard the setting of the cement, causing it to remain soft and reducing its tensile strength and resistance to compression. This retardation, however, had little permanent effect, the cement becoming nearly equal to the unfrozen specimens after the lapse of a few days."

It must be remembered that briquettes made in the laboratory are mixed with the least possible quantity of water, and that all the conditions are favourable to the initial setting and hardening of the cement. On the other hand, concrete made and deposited in the open air, usually contains water in excess; the ingredients are not thoroughly mixed; and interstices, more or less filled with water, remain, affording a lever which the frost is only too ready to use. The difference in hydraulic energy between neat cement, and mortar containing two or three volumes of sand to one of cement, must also be borne in mind.

The latter point is emphasised by the results of experiments carried out by Mr. Fitzmaurice in Nova Scotia during the winter of 1890–1. Exposure to natural frost for four days (out of a total of 28 days) reduced the strength of *neat* Portland-cement briquettes 15 per cent., and of *cement-and-sand* briquettes (1 to 3) from 28 to 35 per cent.; again, exposure for the full period of 28 days reduced the strength of the former 35 per cent., and of the latter no less than 57 per cent.

EFFECT OF FROST ON CONCRETE.—These experiments confirm the results which architects and engineers obtain in actual practice, namely, that mortars and concretes, which,

subject to ordinary temperatures are of satisfactory strength, are, under the influence of frosts, considerably weakened or in extreme cases rendered thoroughly rotten and worthless. These ill effects are observed not only when concrete is mixed and deposited during frost, but also when concrete, mixed and deposited at higher temperatures, is attacked by frost before it has hardened enough to resist it.

Remedies.—I. In the former case,—namely, that of concrete to be mixed and deposited during frost,—two methods are feasible :—

1. Raising the temperature of the concrete-materials, &c., and
2. Adding some substance to the water in order to lower its freezing-point, and so prevent its congelation.

II. In the second case,—namely, that of concrete rightly deposited but likely to be attacked by frost before it has set,—the concrete may often be protected from injury by one of the following three methods :—

1. Lowering the freezing point of the water as in the former case.
2. Hastening the setting and hardening of the concrete, so that it shall be sufficiently strong to resist the frost when it comes.
3. Keeping the temperature around the concrete at a point above 32° Fahr.

I. We will first consider the methods which must be adopted in the case of concrete to be deposited during actual frost.

1. Raising the temperature of the Concrete-materials, &c.—This is undoubtedly the most scientific method which can be adopted, for a rise of temperature hastens the setting and hardening of cements, and does no harm provided that the moisture be not unduly driven off, while, on the other hand, a lowering of temperature retards or stops the processes.

The difficulty of this method, however, lies in its appli-

cation. The most obvious means of raising the temperature of the concrete is to mix it within a building artificially heated, and to use in the mixture warm water instead of icy-cold. Against neither of these can any valid objection be raised on the score of injury to the concrete; each has for its object the mixing of the ingredients under, approximately, those conditions which obtain in summer. The chief objection raised against them is that the heat thus imparted is lost soon after the concrete is deposited in the open air; in fact, that only one-half, and that the simpler half, of the problem has been solved, while the other half, —the protection from frost during setting,—has not been attempted. This objection is valid when the concrete is only thin, as in floors, paving, the walls of ordinary buildings, &c., and the method would be of little avail, if some subsequent means of protection were not adopted. In concrete, however, deposited in large masses, and containing therefore a greater store of heat, the damages wrought by frost are not so great, and the surface-skin, which may be damaged, bears only a small proportion to the mass of the concrete.

Mr. Fitzmaurice, whose tests of frost-bitten briquettes have already been mentioned, proved in actual practice in Nova Scotia that concrete can be safely deposited during frost. In addition to mixing the ingredients in a warm building, he caused the whole of the bed, on which the concrete was to be deposited, to be well steamed, and by raising the temperature in these two ways, he achieved success. If the temperature rose during the day to about 26° Fahr., work was carried on, even though at night the thermometer often registered no less than 42° degrees of frost. He thus* describes the work and states his conclusions:—"Before laying any masonry or concrete all ice was carefully picked out, a steam hose played over all the places where any masonry or concrete was to be deposited, for fifteen or twenty minutes, and each stone was well

* *Proc. Inst. C. E.*, vol. cvii. (1891–2), part i.

steamed. . . . . In the spring, the work which had been done in this way was examined, and some of it picked out; and it was found perfectly sound except the top two inches of concrete. No salt was used in the water on these works. It therefore appeared that concrete and masonry work could be carried on safely in comparatively [*sic*] cold weather if the concrete was mixed under cover, and if, by use of steam or other means, care was taken not to deposit it actually frozen or on material already frozen." On the other hand, a test-block of concrete (1 to 6½) made in the open air during frost and left in the open for four months, was found not to have set at all,—"the whole block could be picked out with a stick." This showed the value of mixing the concrete in a warm room and of using the steam-jet. Certainly Mr. Fitzmaurice has shown architects and engineers one way out of an oft-recurring difficulty.

Another method, which has frequently been recommended for a moderate degree of frost, is based on the fact that *calcium oxide* (quicklime), on being mixed with water, combines with it to form *calcium hydrate*, considerable heat being evolved in the process. In all hydraulic limes, the same action takes place to a greater or less extent. The use of lime in a "hot,"—*i.e.*, unslaked,—state, has for this reason been frequently adopted in frosty weather, and undoubtedly the heat evolved in the mixing of the ingredients does prevent the immediate freezing of the concrete. The disadvantages of the use of unground lime in a hot state have however caused the practice to fall into desuetude. Moreover, common lump lime does not furnish a concrete strong enough for all purposes, and its use cannot therefore be proposed as a sort of diacatholicum. Ground hydraulic lime is of course unslaked, unless it has been exposed to the atmosphere for a time, and some of the varieties yield excellent concrete. The heat, evolved in the mixing of such limes with water, renders the concrete temporarily frost-proof, but, as these limes set slowly, the heat may easily be lost before the setting is suffi-

ciently advanced, and the concrete may after all succumb to the frost. This method, therefore, is not wholly recommendable.

2. Lowering the Freezing-point of the Water used in the concrete is the second method by which concrete can be mixed and deposited during frost. This is the method most frequently adopted, although it is really unscientific, for the setting and hardening of cements are retarded or stopped by low temperatures, while the strength is probably permanently lessened. It may happen therefore that concrete mixed in this way sets so slowly as to be soft for weeks, and that it does not harden to any great extent until the temperature has risen considerably above freezing-point. The method, however, has the advantages of simplicity and economy, for it consists merely in the addition of some substance to the water, or in the substitution of sea-water for fresh water.

The substance most usually employed to lower the freezing-point of water used in concrete, is common salt (*sodium chloride*), but other "salts" have a similar, although, as a rule, smaller effect. Among others, washing-soda (*sodium carbonate*), potash (*potassium carbonate*), saltpetre (*potassium nitrate*), and chloride of lime (*calcium chloride*), may be mentioned. Sodium chloride and sodium carbonate appear to be the only ones which have been tested with cement, and consequently these only can here be considered.

Common Salt (*sodium chloride*, Na Cl).—It may be taken that for every one per cent. (by weight) of salt, which is added to water, the freezing-point of the liquid is lowered 1·08° Fahr.; that is to say, about 13 per cent. of salt will be required to lower the freezing-point of water 14°. It is seldom, however, that more than 7 or 8 per cent. is added to the water used in concrete; if the frost is too keen for this to avail, some other method ought to be adopted or the work stopped.

Professor Baker in his "Masonry Construction" gives the following rule:—"Dissolve 1 lb. of salt in eighteen

gallons of water when the temperature is at 32° Fahr., and add one ounce of salt for every degree below freezing-point." According to this rule, a temperature of 18° Fahr. would require 1 lb. + 14 oz. of salt in every 18 gallons or 180 lb. of water, that is to say, little more than one per cent. by weight. It is clear that Professor Baker's rule underestimates the amount of salt required. Ordinary sea-water, which contains about 2·7 per cent. of common salt and ·8 per cent. of various other salts, freezes at 27·4° Fahr. Had the professor said, "add one *pound* of salt for every degree below freezing-point," he would have been nearer the mark, but still under it.

In Chapter IX. experiments were quoted to show that cement briquettes gauged with salt water are at early dates stronger than similar ones gauged with fresh water, but that the gain is only temporary. No permanent ill effects of any consequence, however, seem to accrue from the use of salt water, provided the salt is not present in excess. Beyond 7 or 8 per cent. (by weight), it is not safe to go.

WASHING-SODA, which consists of crystals of sodium carbonate (Na_2CO_3, $10\ H_2O$), is sometimes used, and Herr Reinhofer considers that it is an excellent preventative of the ill effects of frost. It has not, however, been put to the test of actual practice to the same extent as common salt, and its use cannot therefore be recommended with the same certainty of success. Indeed, experiments by Mr. A. E. Carey, M. Inst. C. E., go to prove that it has a slightly worse influence than common salt, on the strength of Portland cement.

SUGAR has been frequently and warmly recommended as an antidote against frost. It lowers the freezing-point of water to which it is added, and consequently permits work to be carried on when the temperature is below freezing-point, but it is not as effective as common salt, and water containing as much as 20 per cent. of sugar (by weight), cannot apparently be used in more than 5 or 6 degrees of frost. The effect of sugar on lime and cement must be

considered as well as its effect on water, and it is here that it is shown to fail.

It cannot be doubted that the addition of sugar to fat lime increases its strength. This fact has been frequently demonstrated, not only in England but also in India and elsewhere. It appears probable also that sugar in moderate proportions has a beneficial effect on hydraulic limes, especially those of the feebler sorts, but as there would be large elements of uncertainty in every different case, an actual test extending over some months ought really to be made. By the time the test had been carried out, the need for it would have passed for another season.

Portland cement, however, is a material differing vastly from ordinary fat lime and from feebly-hydraulic lime. So delicate are the relations between the components of Portland cement and water, that very little is required to disturb them. A little too much lime or clay, a little sulphuric acid, a little mud or dust, a little impurity in the water—each of these is enough to disturb to some extent the chemical action of setting and hardening, and in extreme cases to prevent the action entirely.

To say the least, the use of sugar with Portland cement is fraught with danger. A very small quantity, of course, may not do much harm; indeed, experiments with a German Portland cement showed that its strength was increased at the end of three months by the addition to the cement of 0·12 to 2 per cent. of pure sugar. More than 2 per cent.,* however, rendered the cement useless. Mr. Henry Faija, who is an authority on Portland cement, says that sugar causes it to "'blow,' *i.e.*, expand, crack, disintegrate, and destroy any work in which it is used." Experiments were made by Mr. A. E. Carey † with the result that out of 24 blocks of cement or cement-mortar containing sugar, 18 fell to pieces before being tested.

* This quantity (assuming the weight of water in the briquettes to be one-fifth the weight of cement) would be 10 per cent. of the weight of the water.

† *Proceedings of the Inst. C. E.*, vol. cvii. (1891-2).

Speaking of these blocks, Mr. Carey says that "in all cases a large quantity of gelatinous tasteless substance was exuded, ... and in setting, the blocks contracted greatly, more especially the samples without sand."

Professor Ira O. Baker, an American, considers that the best Portland cement derives no great benefit from the addition of sugar, but that Rosendale cement (an American natural cement, akin to some of our own natural cements) gains 20 per cent. in tensile strength, when mixed with 0·12 to ·25 per cent. of sugar (by weight), and that lime-mortar gains no less than 50 per cent. when sugar is added to the extent of one-tenth the weight of the lime.

Be this as it may, it is clear that a very small percentage of sugar is enough to destroy the setting properties of Portland cement, and we may therefore conclude that sugar is not a safe material to use with it as a remedy against frost.

After all, therefore, common salt may be considered to be the substance best adapted for lowering the freezing-point of water used in concrete.

II. The second case,—namely, that of concrete rightly deposited but likely to be attacked by frost before it has set,—remains for consideration. In England, this case occurs more frequently than the one which has just been considered. There are several months in the year, during which concrete can as a rule be made and deposited in the daytime, while at night keen frosts interfere with its setting. Three methods of preventing injury being done by the frost, have been mentioned.

1. Lowering the Freezing-point of the Water.—As the application of this method has already been discussed, nothing further need now be said about it.

2. Hastening the Setting and Hardening of the Concrete, so that it shall be sufficiently strong to resist the frost when it comes. Efforts may be made in various directions to hasten the setting of concrete. The first and most important consideration is that of the lime or cement to be used. Other things being equal, the quickest-setting

cement would be the best, but, as other things are not equal, the subject cannot be so easily dismissed. Roman cement sets rapidly, and might be used with advantage for this reason, but on account of its comparative weakness, it will not bind as large a quantity of sand and aggregate as Portland cement. Plaster of Paris and kindred cements set rapidly, but are weaker than Portland cement, and cannot be used in damp places or exposed to the atmosphere on account of their solubility. Portland cement can be obtained of various kinds, some quick-setting, some slow-setting, and others between the two. For the purpose now under consideration, the best quick-setting Portland cement forms the best matrix. If sound, it should be used quite fresh, as stored cement loses energy. (See Chapter VII., pp. 79—81.)

Less sand should be used when the concrete is required to harden rapidly,—less sand and also less aggregate. In fact, the concrete should be richer. Fine sand and dust should especially be avoided, as these retard greatly the setting of cement. No more water must be used than is absolutely necessary.

The steaming-process, which has been already mentioned, would contribute to the desired end by warming the surfaces with which the concrete would come in contact, and so preventing the extraction of heat by them from the mass. The use of water, cement, and aggregate, which had been raised to a moderate temperature (say, 60° or 70° Fahr.), and mixing these ingredients in a warm room, would also hasten the setting and hardening.

A considerable proportion of the heat in concrete, which has been mixed as described above, can be retained by covering it with straw, sacks, &c., kept in place by planks, or with bags filled with hay, straw, saw-dust, or other good non-conductor of heat. It is possible too that floor-surfaces could be efficiently protected from injury by covering them to the depth of one or two inches with water, although this would have the effect of retarding the setting. We know that in England the ice on our ponds is seldom thick

enough to bear skaters until there have been several days of continuous frost. Water freezes from the surface downwards, and it would take several days of very severe frost before concrete, covered two or three inches deep with water, would be reached by it. Mr. Fitzmaurice found that the excessive cold of a Nova Scotian winter injured to the depth of only two inches, concrete which had been mixed under cover and deposited when the steam-jet had been freely used; evidently by the time the frost had penetrated to that distance the inner portion had hardened sufficiently to be able to resist it.

The temperature at the bottom of deep trenches is very many degrees higher in winter than the temperature at the surface of the ground; and good concrete deposited in them and immediately covered with straw, &c., as already indicated, or even with sand and rubbish, would probably take no harm.

3. Finally, concrete can be protected by *keeping the surrounding temperature above freezing point.* This is mentioned rather because it is a possible method of attaining the desired end, than because it is one likely to be adopted. The method would in practice prove too expensive for work in the open air, but it might advantageously be employed for work under cover. For instance, in the case of concrete floors to be laid in existing buildings, or in new buildings which have been roofed and fitted with windows, the temperature could be raised without very great difficulty. But one most important consideration must not be overlooked—*dry heat is extremely injurious to concrete.* Therefore, fires are not to be recommended unless the concrete is kept moist by being covered with damp sand or sawdust, or in some other way. Steam hastens the setting of concrete, and consequently this would be the most suitable agent for raising the temperature.

The various methods of depositing and protecting concrete during frost have now been mentioned. In conclusion it may be said that the labourers will have to be considered, and it is possible that in many cases they will

refuse to work during extremely cold weather, for they are very human, and will thus settle the question of "concrete-depositing during frost" in a very summary fashion of their own. If the materials were mixed in a warm building, as has been here advocated, and the labourers worked by turns inside the building and outside, their objections might, perhaps, be overcome.

Expansion and Contraction.—The expansion of concrete in hot weather and its contraction in cold weather are now well-known facts, and ought to be guarded against. In their designs for bridges, &c., engineers are compelled to consider carefully the expansion and contraction of iron and steel under changes of temperature, and it is little hardship for us to have to take into consideration the variation of concrete, which is probably less than that of iron. Ignorance, however, of the facts has led to the destruction or disfigurement of much concrete paving, walling, &c.

At one time it was thought that cement expanded largely in setting, and that this was the cause of many cracks in concrete. Undoubtedly, bad cement may expand or contract in setting, but in Chapter VII. we showed that the expansion of good air-slaked Portland cement is almost inappreciable. The cracks in concrete walls and paving are most commonly due to changes of temperature, the cracks having a tendency to open in winter and close in summer; for this reason Mr. Thomas Potter prefers laying concrete paving in winter and protecting it with straw, sacks, or other covering, as by this means he considers that the concrete is laid at the time of its greatest contraction, and that any change of temperature simply causes it to expand and compress itself to a greater density. This theory is, at any rate, ingenious.

In continuous concrete walls, paving, &c., of considerable length, subject to the full effects of the year's changing temperature, cracks frequently occur at moderately regular intervals. In retaining walls and paving, the cracks are objectionable, mainly because they are unsightly, but in

flat roofs, &c., the cracks are a source of danger and give ready entrance to unwelcome rain. The usual method of preventing these cracks is to lay the concrete in more or less distinct masses of moderate size, but different means of doing this are adopted for different purposes, and these will be severally considered in the chapters on walls, paving, and roofs.

The fine cracks, known as "hair cracks" or "crazing," which sometimes appear on the surface of concrete, are probably due to the use of a finishing coat too rich in cement. Mr. A. C. Davis * says that they may occur "in work carried out with the soundest and best-made cements," and that "no cement should be used in the dressing of concrete work without being well mixed with sand or other very fine aggregate."

* See article on "Portland Cement" in *The Stone Trades Journal*, March, 1904.

CHAPTER XV.

SOME CHARACTERISTICS OF CONCRETE.

Porosity—Weight (Table XX.)—Compressive strength (Table XXI.)—Resistance to Fire.

Porosity.—Water-tight concrete is sometimes required, as for the bottoms and sides of tanks, flat roofs, and the ground-layer under a building. It may be said at once that all concrete is not by any means water-tight; the porosity may be due to the nature of the aggregate, as in the case of coke-breeze, soft bricks, friable stone, &c., or may be caused by the bad proportion of the ingredients, which allows voids in the concrete, or may be due to insufficient ramming.

The use of too little water in mixing, also makes concrete less dense than it ought to be. In proof of this statement we may adduce an experiment made by Mr. H. K. Bamber.* He prepared two cubical blocks of concrete, measuring 18 in. each way; one was mixed with the full quantity of water required,† the other with only half the quantity. Into each block a short iron pipe was inserted, reaching to the middle, and when the blocks were set, an iron pipe 30 ft. high was screwed to each short piece, and on the top a tank was placed and filled with sea-water. In half-an-hour a milky fluid began to exude from all sides of the block which had been mixed with insufficient water, while no water or milky fluid passed through the other during three days on which the pressure was continued.

* *Proceedings of the Inst. C. E.*, vol. cvii. (1891-2).
† See chapter ix., p. 97 *et seq.*

Most concrete, however, will allow the percolation of water under pressure, but Mr. Faija found that the forced percolation of water through cement-mortar (1 to 3) improved rather than injured its strength, and that the pores in the mortar gradually filled up, so that at the end of about three months the water ceased to pass through it.* Mr. Cash † found that when water with a head of 20 ft. was applied to a plug of concrete 12 in. thick, composed of Portland cement, coarse sand and gravel (1 + 2 + 5), no less than 165 ozs. passed through in the first twenty-four hours, while only 5 ozs. passed through a 12-in. plug made of similar materials in the proportion of 1, 2, and 7, but rendered with cement-mortar (1 to 3), "trowelled on as thinly as possible." On the fifty-fourth day 42 ozs. passed through the former, and 4 through the latter. This shows the great advantage of rendering concrete with cement or cement-mortar, or, in the case of ground-layers and roofs, with asphalt. Indeed, so advantageous is some kind of rendering to concrete intended to resist pressure of water, that it ought never to be omitted. It will be found more economical to use a somewhat poorer concrete well rendered on the face, than to try to obtain a concrete impervious throughout its bulk.

The proportions of ingredients required to produce solid concrete have been considered in Chapter XII. See also Table XVIII., p. 138. The points to be borne in mind in making impervious concrete may be summed up thus:—(1) the voids in the aggregate must be as small as possible, and must be rather more than filled by the mortar, which must itself be impervious; (2) more cement must be used in proportion to the aggregate than for ordinary work; (3) the full quantity of water must be added; and (4) the concrete must be well rammed, and brought in that way to a good even surface. In any case, however, a thin trowelled coat ought to be added.

All limes and cements are not equally suitable for con-

* *Society of Engineers*, 1889.

† *Proceedings of the Inst. C. E.*, vol. cvii. (1891-2), part i.

crete intended to be waterproof. None of them are as impervious as asphalt, but Portland cement approaches it most nearly.

Professor Tichborne, F.I.C.,* found the relative porosity of certain mortars and cements to be as follows :—1. Common lime-mortar (1 to 2), 100 ; 2. Plaster of Paris, 75 ; 3. Roman cement, 25 ; 4. Portland cement, 10. Asphalt is, he considers, a perfect septum.

WEIGHT.—The weight of concrete is sometimes important; in the case of floors, for instance, lightness is a point which ought to be specially considered in connection with the strength. In external walls there can, as a rule, be no objection to heavy concrete, but in internal partition-walls, especially on upper floors, lightness is an advantage. The results of tests by Mr. Grant on the weights of the various concretes mentioned in Table XVI., are as follows :—

TABLE XX.—WEIGHT OF PORTLAND-CEMENT CONCRETE IN LBS. PER CUBIC FOOT.

Number.	Aggregate.	Six to One.		Eight to One.		Ten to One.		Ratios of	
		Com-pressed.	Not Com-pressed.	Com-pressed.	Not Com-pressed.	Com-pressed.	Not Com-pressed.	Weight.	Strength.
1	Ballast	143·2	138·8	142·8	139	141·4	137·6	99	49·1
2	Portland stone.	135·2	125·6	130·5	125	131·5	129·2	91·3	100
3	Granite	148·2	139·2	144·8	139·6	139·2	135·7	99·4	68·6
4	Pottery	128·8	126·8	129·2	125·6	128·7	125·2	89·8	74·4
5	Slag...............	120·6	118·4	113·6	109·8	112	110	80·4	56·4
6	Flints	132	121·6	131·6	123·2	129·2	121	89·1	56·3
7	Glass	148	142	144	138·4	143·2	135·6	100	58·3

We learn from this table that compression increased the weight of the blocks about 4 per cent., while, as we have already shown, it increased the strength about 27 per cent. The difference in weight between the 6 to 1 and 10 to 1 concretes is only about 3 per cent., the latter being the

* Paper read at *Sanitary Congress*, Worcester, 1889.

lighter on account of the greater amount of voids therein. The last two columns are interesting; they show that ballast and glass make very heavy but very weak concrete, and that Portland stone and pottery make concrete heavy but strong, Portland stone giving the greatest strength of all.

The weight of concrete varies also according to the amount of sand it contains; a concrete having too little sand will be more porous, and, consequently, lighter than one containing more sand, other things being equal.

Again, the weight of different kinds of the same class of aggregates varies largely; *e.g.*, different sandstones vary in weight from about 116 lbs. to 170 lbs. per cubic ft., and the weight of the concrete made with them will vary in the same proportion.

The different weights of different limes and cements must also be taken into consideration, Portland cement being the heaviest.

For these reasons, it is impossible to give a table of weights of concrete which shall be of much value. It may, however, be said that Portland-cement concrete, having coke-breeze as its aggregate, will weigh from 70 to 80 lbs. per cubic ft., although concrete made with crushed furnace-clinker may reach 118 lbs. per cubic ft.; burnt-clay concrete about 100 or 115 lbs.; brick concrete about 120 lbs.; brick concrete, containing $1\frac{1}{2}$ or 2 volumes of sand, 125 to 130 lbs.; gravel or shingle concrete from 130 to 145 lbs.; and granite concrete from 135 to 160 lbs. Concrete made with broken limestone or sandstone will vary from 110 to 150 lbs., according to the weight of the stone.

COMPRESSIVE STRENGTH.—The compressive strength of Portland-cement concretes having different aggregates has already been considered, the results of Mr. Grant's tests having been given in Table XVI., p. 127. The compressive strength of concretes having the same aggregates, but different matrices, remains to be noticed, and here again we are indebted to Mr. Grant for a valuable series of tests.

Altogether he made 350 6-in. cubes of concrete having

varying proportions (by volume) of lime or cement and aggregate; the aggregate in each case consisted of gravel and sand (apparently mixed together just as obtained from the pit or river), weighing 137 lbs. per bushel; ten blocks were made of each kind, were kept in air, and crushed at the end of twelve months. Table XXI. has been calculated and framed from Mr. Grant's figures.*

TABLE XXI.—COMPRESSIVE STRENGTH OF CONCRETE IN TONS PER SQUARE FOOT.

No.	Limes and Cements.	Weight per Bushel.	Proportion of Lime or Cement to Gravel and Sand. 1 to 6	1 to 8	1 to 10	1 to 12	Average ratios of Strength.
		lbs.	Tons.	Tons.	Tons.	Tons.	
1	Grey lime	...	10·2	4·6	5·2	...	8·7
2	Grey lime Selenitic	...	18·5	7·6	8·1	...	14·9
3	Lias lime	...	11·4	11·1	11·5	...	14·8
4	Lias lime Selenitic	...	17·2	19·6	10·2	...	20·3
5	Lias lime	...	23·0	10·7	8·5	...	18·3
6	Selenitic lime	...	26·6	15·3	13·5	...	24
7	Selenitic Rugby Lias	...	37·1	34·2	21·1	...	40
8	Selenitic Aberthaw lime	...	34·1	21·8	15·4	...	30·9
9	Rugby Lias Cement	74	17·2	10·7	5·8	...	14·6
10	Portland Cement	114	100·7	76·4	53·5	37·1	100†
11	Portland Cement	120	86·4	91·7	52·2	29·1	100†

Mr. Grant's tests show that 1 to 8 concrete is about three-fourths the strength, 1 to 10 about one-half the strength, and 1 to 12 about one-third the strength of 1 to 6 concrete. These are the average ratios; individual cases are sometimes very different from these; for instance, grey-lime concrete (1 to 8) appears weaker than (1 to 10), the Lias-lime concrete No. 3 gives practically equal results with the three different proportions, and the Portland-cement concrete No. 11 has less strength when used in the proportion of 1 to 6 than when 1 to 8. But we must look on these instances as abnormal. It is clear that the *lime*-con-

* For the tensile strength of the same limes and cements, see Table I., page 20.

† Not including the 1 to 12 mixtures.

cretes,—namely, Nos. 1, 3, and 5,—differ most widely from the average ratios. And this is one of the disadvantages of lime-concrete; one is never as sure of its behaviour as of that of Portland cement.

The regulations of the London County Council require the foundations of walls to be formed of good concrete, composed either of 1 part lime and 6 parts aggregate, or of 1 part cement and 8 parts aggregate. When these proportions are considered in the light of Mr. Grant's experiments, it is clear that the lime-concrete allowed by the regulations is far inferior in strength to the cement-concrete, if the cement be Portland.

If we compare the 1 to 6 lime-concretes, with the 1 to 8 cement-concretes, we find that the best Lias-lime concrete tested by Mr. Grant (No. 5) is less than one-third the strength of the worse Portland-cement concrete, and only one-fourth the strength of the better. Portland-cement concrete (1 to 12) is shown to be better than the best Lias-lime concrete (1 to 6). Mr. Bernays, at Chatham Dockyard, found that 1 to 12 Portland-cement concrete cost the same as 1 to 6 Lias-lime concrete, and was stronger and more uniform. There is no doubt that the regulations of the London County Council favour the use of inferior matrices in concrete.

For the relative cost, per unit of strength, of lime and cement-mortars, see Table III., page 23.

Resistance to Fire.—The resistance of concrete to fire varies greatly according to its composition. Portland cement is the best matrix, and coke-breeze, brick, and slag are among the best aggregates, in this respect. The old fiction, that concrete is fire-proof, has been exploded for some time, and there seems a disposition nowadays to go to the opposite extreme and to say that it is scarcely fire-resisting. Attempts to protect iron by means of concrete are looked upon as old-fashioned, and inventors are turning all their attention to fire-clay tubes and blocks. The expense of these is against their adoption in the commoner sort of buildings, and it is certainly better in these cases to

provide an incombustible fire-resisting floor of concrete and iron than a combustible fire-assisting floor of wood. The former will be more expensive than the latter, but it will be considerably cheaper than the floor containing fire-clay tubes.

The actual amount of heat conveyed to iron bars through

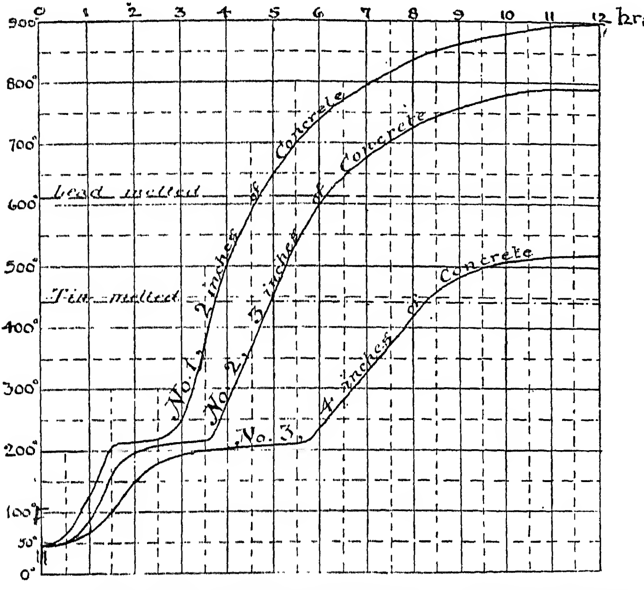


Fig. 8.—Diagram showing the Heat imparted to Iron Bars protected by 2, 3, and 4 inches of Concrete, when placed over a Furnace for 12 hours.

2, 3, and 4 inches of concrete, has been ascertained by Mr. Thaddeus Hyatt. The thermal diagram, figure 8, shews the results obtained by him, and is a modification of the one given in his book on concrete.* A furnace, about 18 inches

* "Experiments with Portland-Cement Concrete combined with Iron," by Thaddeus Hyatt.

wide internally, was constructed, its top being formed of concrete. The width of the concrete over the fire-box of the furnace, was divided into three parts, each part having an iron bar let into its upper surface; the right-hand bar was protected underneath by 2 in. of concrete, the middle one by 3 in., and the left-hand one by 4 in. The composition of the concrete is not definitely stated, but it was presumably the same as in some other experiments, namely, 1 part Portland cement and 2 parts crushed stock bricks. The age of the concrete also is not stated. The fire in the furnace was kept burning for 12 hours, "an intense heat being maintained the whole time, and the temperature noted every few minutes."

"It will be observed on examining the chart that the thermal lines, as they approach the boiling point of water remain in that vicinity for some considerable time, the explanation of which is that this length of time was required for the evaporation of a certain amount of free moisture contained in the concrete, after which the temperature again continued to rise as before. It will be also noted that the thermal line of the 3 in. thickness of concrete is higher than a mean between the 2 in. and 4 in. thicknesses, which may be accounted for on the ground of its position at the centre of the top of the furnace."*

The diagram shews "that in 3 hours after the fire was lighted, the temperature of iron protected by 2 in. of concrete was 250°; in 5 hours, it was 650°, and, finally, at the end of 12 hours 900°, or red hot in the dark; while the iron protected by 4 in. of concrete for $5\frac{1}{2}$ hours did not exceed 212°; in $8\frac{1}{2}$ hours the temperature was 450°, and at the end of 12 hours, 550°, or less than the melting point of lead."*

We are not told whether the concrete remained perfect at the end of the experiment, or not, but we presume that it did, otherwise Mr. Hyatt would have noted the damage. Apparently, however, he wished to make assurance doubly

* "Experiments with Portland-Cement Concrete combined with Iron," by Thaddeus Hyatt.

sure, for a second furnace was built 5 ft. long and 2 ft. wide internally, the top being formed with a slab of concrete (presumably of 1 cement to 2 crushed brick) which had a bearing of 6 in. at each end of the furnace but was quite free at the sides. In the middle of the concrete wrought iron was embedded in gridiron form (see Fig. 30, p. 271), "3 in. of concrete being above, and 3 in. below the metal. Loose bricks were piled upon the furnace top until a load was obtained of 300 lbs. to the foot square over the whole surface,* the deflection being with this load $\frac{1}{32}$ of an inch in a span of 5 ft. The fuel was arranged to form an incandescent bed 6 in. thick at 12 in. below the under face of the concrete slab. The fire being kindled at six o'clock in the morning, had by eleven become an intense heat perfectly uniform over the entire surface, and the bottom of the concrete was also at a glowing red heat all over. At this intensity the fire was kept up until 4 p.m., a period of ten hours from the lighting of it. During this time the slab had deflected $\frac{3}{8}$ of an inch. A stream of cold water was now thrown forcibly against the bottom of the slab for a period of 15 or 20 minutes, by means of a garden force-pump, and the load then removed. On examining the underside of the section it was found uninjured; and the next morning, being then entirely cold, the deflection had disappeared, the slab having returned to its former level. In order to confirm these results, a second trial was made; this time the load was left upon the slab, which during the firing deflected as before, but upon cooling returned to its original level, *lifting the load with it.* In proof of the heat of the furnace it may be mentioned that in the course of this experiment the faces of all the side bricks in actual contact with the fire were melted."

These experiments seem to shew that good concrete will resist fire to a very considerable extent, and that a thickness of 2 or 3 in. will effectually prevent iron from being damaged in (at least) moderately severe conflagrations.

* In addition to the weight of the concrete.—G.L.S.

And it must not be forgotten that in those buildings where the goods, &c. are not particularly inflammable and numerous, a floor, which will resist fire for a few minutes only, is frequently the means of confining the fire until extinguishing appliances can be brought Into use, and in this way of preventing the destruction of the premises.

The testimony of Mr. Wm. Swanton of the Metropolitan Salvage Corps is valuable. To a Committee of the *Society of Arts*, which was inquiring into "the means of protecting the Metropolis against conflagration," he said, "the effect of fire on concrete is scarcely perceptible in ordinary fires, especially when the ceilings and floors were formed of that material; but in very large fires the concrete would split into irregular forms, but not until it became almost red-hot, and was subjected to the action of cold water thrown on it, and even then the result could not be compared to that of ordinary stone."

Captain Shaw, however, expressed a different opinion. The collapse of a number of concrete floors in burning buildings led him at one time to forbid his men to enter during a fire any room which had a concrete floor over it.

And more recently, in a paper read at the *International Fire Prevention Congress* held in London in June, 1903, Mr. Arthur Pordage, firemaster of Edinburgh, stated that his own experience led him to the conclusion that a well-constructed wooden floor with plastered ceiling is less dangerous than many of the so-called "fire-proof" structures of steel and concrete. In the discussion on this paper, Mr. E. G. Rivers (of His Majesty's Office of Works) stated that concrete, reinforced with a meshwork of wires, had been tested with satisfactory results, but added—"many concretes . . . . are absolute failures from a fire-resisting point of view; if a rotten aggregate, or an aggregate which calcines under heat, is used, failure must be looked for; a typical aggregate is one which has already been vitrified, such as crushed furnace slag."

CHAPTER XVI.

CONCRETE BEAMS.

Unsuitability of the material—Experiments on beams (Table XXII.) —Formulas I. to VII.—Increase of strength due to fixing the ends—Mr. Colson's Tests—Example.

UNSUITABILITY OF THE MATERIAL.—Concrete is not a suitable material for resisting transverse stress. Like cast iron, its tensile strength is far inferior to its compressive strength; indeed the difference between the tensile and compressive strength of concrete is greater than in the case of cast iron. The disadvantages, therefore, which have led to the disuse of the latter material in the form of beams, are even more marked in concrete, and are an important factor in determining the uses to which concrete can safely and economically be put. Like stone, concrete is most safely and economically employed in such a manner as to be subject to a compressive and not a transverse stress. And just as stone lintels over large openings are cumbrous and dangerous, liable to crack with the least irregular settlement of the supports, so also concrete. With firm abutments, both materials can be used with greater safety and economy in the form of arches. But it is not always possible so to arrange our materials as to have them subject solely to the stress they are best able to resist, and it therefore happens that in foundations, floors, lintels, &c., concrete is frequently employed subject in a great measure to transverse stress. For this reason it behoves us to consider the strength of concrete beams.

TABLE XXII.—TRANSVERSE STRENGTH OF CONCRETE AND OTHER BEAMS, SUPPORTED AT ENDS.

Number.	Composition. Portland Cement.	Sand.	Aggregate.	Age in Days.	Breadth.	Depth.	Clear Span.	No. of Tests.	Loaded at	Average Breaking Weight.	Reduced to Breaking W. at Centre.	One-half* Weight of Beam between supports.	Total Central Load.	Constant.	Authority.
					In.	In.	In.			Cwt.	Cwt.	Cwt.	Cwt.		
1	1	0	1 coke breeze	7	3	5	72	1	centre	3·85	3·85	0·22	4·07	5·86	A
2	1	0	2 crushed brick	b	12	8	60	1	,,	13·25	13·25	1·83	15·08	1·76	A
3	1	2 c	...	90	,,	12	36	2	central 6″	155	142·08	1·55	143·63	4·48	B
4	1	2 d	...	,,	,,	,,	,,	3	,,	113·33	103·88	1·55	105·43	3·29	B
5	1	0	4 clean breeze	43	30	6·5	59	1	central 16″	66·32	57·32	2·12	59·44	4·15	C
6	1	0	4 broken brick...........	,,	,,	6	59·5	1	,,	40·52	35·07	2·53	37·6	3·11	C
7	1	0	4½ crushed slag (¾ in.).	15	29·5	4·5	27	1	central 6 in.	22·48	19·98	1·22	21·20	1·43	I
8	1	0	4½ ,, furnace clinker (¾ in. down to fine).	,,	18	9	,,	1	,,	69·15	61·47	1·33	62·80	1·74	I
9	1	0	,, ,, ...	21	,,	,,	,,	1	,,	104	92·44	,,	93·77	2·60	I
10	1	0	6 ,, ,, ...	14	,,	,,	,,	3	,,	52·64	46·79	,,	48·12	1·34	I
11	1	0	,, ,, ...	21	,,	,,	,,	1	,,	57·80	51·38	,,	52·71	1·46	I
12	1	2§	6 ,, ,, ...	,,	,,	,,	,,	2	,,	18·30	16·27	,,	17·60	0·49	I
13	1	0	5 shingle	139	12	12	36	1	centre	85·62	85·62	1·77	87·39	2·73	D
14	1	1	5 ,, ...	,,	,,	,,	,,	1	,,	68·74	68·74	1·91	70·65	2·21	D
15	1	2	5 ,, ...	,,	,,	,,	,,	1	,,	43·61	43·61	1·84	45·45	1·42	D
16	1	3	5 ,, ...	,,	,,	,,	,,	1	,,	27	27	1·76	28·76	0·89	D
17	1	2	6 gravel..........	90	12	12	36	3	central 6″	46·67	42·78	,,	44·54	1·39	B
18	1	2	2 broken stone, 1½ in. . 4 ,, ,, 3½ in. .	,,	,,	,,	,,	3	,	52·5	48·12	,,	49·88	1·56	B
19	1	2	6 ,, ,, 1½ in. .	,,	,,	,,	,,	3	,,	40·83	37·43	,,	39·19	1·22	B
20	1	0	9 shingle	95	12	12	18	1	centre	83·06	83·06	0·77	83·83	1·31	D
							36	1	,,	38·33	38·33	1·53	39·86	1·24	
21	1	1	8 ,, ...	,,	,,	,,	18	1	,,	71·18	71·18	0·92	72·10	1·12	D
							36	1	,,	38·33	38·33	1·84	40·17	1·25	
22	1	2	7 ,, ...	,,	,,	,,	18	1	,,	56·16	56·16	0·94	57·10	0·89	D
							36	1	,,	30·15	30·15	1·88	32·03	1·00	

TABLE XXII.—(*continued*).

Number.	Composition. Portland Cement.	Sand.	Aggregate.	Age in Days.	Breadth.	Depth.	Clear Span.	No. of Tests.	Loaded at	Average Breaking Weight.	Reduced to Breaking W. at Centre.	One-half* Weight of Beam between supports.	Total Central Load.	Constant.	Authority.
					In.	In.	In.			Cwt.	Cwt.	Cwt.	Cwt.		
23	1	3	6 shingle	95	12	12	18	1	centre	30·28	30·28	0·93	31·21	0·49	I
							36	1	,,	20·04	20·04	1·86	21·90	0·68	
24	1	3	6 ,, screened ..	28	21	9	99	1	central 6″	5	4·85	6·57	11·42	1·00	
							45	1	central 12″	20·88	18·35	3·08	21·43	0·85	
							45*e*	1	,,	13·6*e*	11·92	,,	15	0·59*e*	
25	1	4	5 ,, ...	95	12	12	18	1	centre	24·91	24·91	0·84	25·75	0·40	
26	1	4	5 ,, ...	139	,,	,,	36	1	,,	23·71	23·71	1·69	25·4	0·79	
27	1†	1	½ gravel (¾ in.). 3 broken stone (1 in. to 4 in.)	182	6	12	36	1	central 12″	72	66·05	0·75	66·8	4·17	F
28	1‡	1	...	100	2	2	4	2	centre	5·22	5·22	*a*	5·22	3·91	G
	Natural Stones.														
29	Portland Stone (brown)				4·5	6	36	...	,,	17	17	0·38	17·38	5·79	H
30	,, ,, (white)				,,	,,	,,	...	,,	12·67	12·67	0·36	13·03	4·34	
31	Box-ground (limestone)				,,	,,	,,	...	,,	4·25	4·25	0·31	4·56	1·52	
32	Corsham Down (limestone).................				,,	,,	,,	...	,,	3·18	3·18	0·3	3·48	1·16	

* The weight of the beam itself is part of the load, and must, therefore, be considered in the calculations, otherwise grossly inaccurate results would sometimes be obtained; *e.g.*, the weight of the first beam of the three numbered 18 is nearly three times as much as the load put upon the beam. The weight of the beam must really be considered as a distributed load, and as the stress of a distributed load is only one-half that of a central load, one-half the weight of the beam is given in the column.

† Slag cement. ‡ Roman cement. § Clinker ground to size of coarse sand.

a. Weight too small to be considered. *b.* "Two or three months"; the various ages of the beams should be carefully noted.

c. Coarse sand. *d.* Fine sand. *e.* Part of a larger beam which fell before it had properly set, and was, therefore, probably strained.

Authorities.—A, David Kirkaldy; B, John Kyle; C, Col. Crozier; D, Darnton Hutton; E, C. Colson; F, Wm. Kidd; G, Q. A. Gillmore; H, Gwilt; I, S. R. Lowcock.

Experiments on Beams.—The strengths of limes, cements, and mortars have been given in previous chapters, and from these the transverse strength of concrete has often been calculated, but these data are at the best unsatisfactory. Even transverse tests of mortar (see Table XI., page 72) are not to be relied on. They are like the results obtained by Tredgold and other early experimenters on the transverse strength of small pieces of wood; the strength of beams, calculated from the results thus obtained, was always placed too high. In order to obtain an approximate estimate of the proper strength of concrete beams, we must deduce our constants from the breaking weights of similar beams. Table XXII. gives a few results of that kind, together with the constants or co-efficients of rupture, deduced from the same according to the formula,—$W = \frac{2}{3} C \frac{BD^2}{L}$, which, being transposed, gives $C = \frac{3WL}{2BD^2}$.

The first thing which strikes us on a perusal of the preceding table is the great difference in the strength of the various beams. If, however, we make due allowance for the different proportions of cement and aggregate in the several concretes, and for the difference in their age at the time of testing, we find that the variation in strength is really not excessive, although doubtless sufficient to cause any calculations based on some of the highest of the constants to be viewed with a certain amount of suspicion. The weakening effect of sand is particularly noticeable; compare 11 with 12, and also examine the two series of tests 13 to 16 and 20 to 26. The dissimilarity of the results is also due in part to the fact that the experiments were carried out at different times by different persons, with different cements and aggregates.

It is, indeed, impossible from existing data to calculate with accuracy the value of C for variously-proportioned concretes; a long series of experiments would be required before this could be done. Until such experi-

ments have been made, architects must perforce proceed more or less empirically in the construction of concrete foundations, floors, roofs, &c., but the foregoing table will give a general idea of the constants to be employed in making calculations for such purposes.

In Table XI., page 72, the transverse strength of Portland cement, neat and with different proportions of sand, was given, and the constants were shewn to vary from 12·3 for neat cement to 1·8 for mortar consisting of 1 part cement to 5 parts sand. Roman-cement mortar (1 to 1) was between one-half and one-third the strength of similar Portland-cement mortar.

It will be noticed that the transverse strength of good ordinary concrete compares favourably with that of some natural stones. Specially-prepared concrete, of course, gives even better results :—for instance, at the Croft Concrete Works, a flag is now bearing without deflection or sign of distress, a load which, *had it been the breaking weight*, would have yielded a constant of no less than 3·7. For beams and floors, a carefully prepared concrete, rich in cement, is preferable to a weak concrete, as the strength is not only greater but also more uniform, and the dead-weight of the structure is considerably less.

FORMULAS.—The strength of rectangular beams is considered in several text-books, and it will be sufficient here to repeat the usual formulas, from which the strength or dimensions can be calculated. W = breaking weight in cwt.; B = breadth in inches; D = depth in inches; L = length or clear span in inches; and C = constant or coefficient of strength.

To find the strength of rectangular beams *supported* at the ends and loaded *at the centre*, we have the formula

$$W = \frac{2}{3} C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(I.)}.$$

For beams *supported* at the ends and *uniformly* loaded, we have

$$W = \frac{4}{3} C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(II.)}.$$

For beams *fixed* at the ends and loaded *at the centre*, we have

$$W = \frac{4}{3} C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(III.)}.$$

For beams *fixed* at the ends and *uniformly* loaded, we have

$$W = 2 C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(IV.)}.$$

For beams *fixed* at one end, *supported* at the other, and loaded *at the centre*, we have

$$W = \frac{8}{9} C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(V.)};$$

and for similar beams *uniformly* loaded, we have

$$W = \frac{4}{3} C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(VI.)}.$$

For beams *fixed* at one end only, and free at the other, and *uniformly* loaded, we have

$$W = \frac{1}{3} C \frac{BD^2}{L} \quad \ldots \quad \ldots \quad \text{(VII.)}.$$

These are the formulas given by Professor Unwin, although somewhat differently expressed. It will be noticed that formulas II., III., and VI. are the same, and that the strength of centrally-loaded beams with fixed ends is 100 per cent. more than when the ends are supported, while that of uniformly-loaded beams with fixed ends is only 50 per cent. more than with the ends supported. In the former the ratio is as 100 is to 50, in the latter as 100 is to $66 \cdot \dot{6}$.

Experiments go to prove that these ratios do not hold good for concrete beams; fixing the ends of these seems to convert them into flat arches of considerable strength, but no definite rule can yet be formulated on account of the paucity of experiments.

Increase of Strength due to Fixing the Ends.—Prof. Anderson, in his "Strength of Materials," says:—"The increase of strength, due to secure fixing of the ends, has

been variously stated" [from once-and-a-half to twice the strength when supported]; . . . . "but it is obvious that the value will depend upon so many conditions that it is impossible to say precisely what it is beforehand; it must, therefore, be considered as doubtful, unless all the conditions are known definitely; at the same time, the importance of secure fixing, wherever it can be employed, should be noted."

In the case of concrete floors, laid over the walls when these have reached the proper height, and subsequently built upon, we have a degree of fixity apparently far in excess of that attained when the concrete is simply let into chases in the walls, or supported on corbel courses projecting therefrom. In the former case the ends, or edges of the floor are securely fixed, provided, of course, that the weight of wall above the floor is enough; but in the latter case they are, to some unknown extent, simply held in addition to being supported.

It may be thought that floors resting on corbel courses are supported, and nothing more, but this is not the case, for the concrete abuts against the walls, and is prevented by them from spreading; in this way, the floor becomes really a flat arch or (contradiction in terms) a flat dome, and may carry more than twice as much as if the ends were merely supported.

Mr. Colson's Tests.—This, at any rate, has been shown by experiment to be the case with concrete beams tested by Mr. C. Colson, and described by him in the *Proc. Inst. C. E.*, vol. liv. (1877–8), part iv.

Two concrete beams were formed, 9 ft. long, 21 in. wide, and 9 in. deep, supported $4\frac{1}{2}$ in. at each end, the concrete being composed of 1 part Portland cement, 3 parts sand, and 6 parts screened harbour shingle. The ends of one of the beams (No. 1) were prevented from spreading by counterforts as at A., Fig. 9; while those of the other beam (No. 2) were simply supported as at B. At the end of fourteen days the scaffolding under the concrete was very carefully removed, when beam No. 2 at once broke with its

own weight, while beam No. 1 exhibited "no sign whatever of weakness."

"After remaining unsupported for a further period of sixteen days, the beam (No. 1) was tested by placing weights on the centre. Under 0·25 ton a faint crack was observed at the centre through the whole width of the beam; with 0·635 ton it had increased as nearly as could be determined to half the depth, viz., $4\frac{1}{2}$ in., and opened to about $\frac{1}{16}$ in. at the lower surface. The full extent of the fracture probably exceeded this, although not apparent on the surface. No perceptible upward extension of the fracture could, however, be detected after the imposition of the

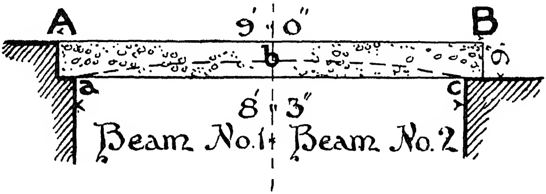


Fig. 9.—Elevation of Two Beams tested by Mr. C. Colson.

weight last referred to. The load at the centre was ultimately increased to 1·292 ton, when the beam broke. This experiment shows the necessity of guarding against the possibility of lateral movement, in the slightest degree, in the supporting girders of a floor; in this case by so doing the supporting power of the beam was materially increased. It also shows that the mass within the dotted line *a b c* [Fig. 9] adds nothing to the strength of the beam when confined at the ends, as proved by the crack appearing so soon after the commencement of the loading."

Three other concrete beams, of exactly similar composition to the two just mentioned, had previously been made and tested by Mr. Colson; the results of these tests are given in Table XXII., No. 24. The average value of C for two of these beams is ·92, the ends being simply supported, while the value of C for the beam confined at the ends, if

we use the formula for a *supported* beam, is no less than 2·6, or nearly three times as much. According to the usually accepted formulas for the strength of beams, fixing the ends, at the most, only doubles the strength (see formulas I. and III.), but in this case *merely confining the ends* effected a considerably greater increase.

If we may judge from Mr. Colson's experiment, the great compressive strength of the material enables a flat concrete beam, when the ends are simply confined, to become to all intents and purposes an arch capable of carrying as great a load as if the ends were securely fixed. This, however, needs further proof, and, until this is forthcoming, care should be taken that concrete subject to transverse stresses, should have the edges as securely fixed as possible, in order that full advantage may be taken of the increase of strength, be it more or less, which such fixing is known to insure.

EXAMPLE.—An example of calculating the dimensions of a concrete beam for a given span and weight may be of use to the student. Let us take the case of a floor with two opposite edges *fixed* in walls, the remaining two edges being free. Required the thickness of concrete to carry a distributed load of 1 cwt. per sq. ft. (in addition to the weight of the concrete) over a span of 12 ft. and width of 10 ft.,—two opposite edges fixed,—at the age of 6 weeks; the concrete to be composed of 1 part Portland cement and 4 parts clean breeze.

The weight of the concrete itself must be considered as part of the load, but, as its thickness is unknown, its weight also is unknown, and therefore the total load on the concrete cannot be stated offhand. On account of this the calculations are rendered more intricate. The total weight of the slab, assuming the concrete to weigh $\frac{3}{4}$ cwt. per cub. ft. will be $\frac{\text{D } (i.e., \text{ depth in ins.})}{12} \times 12 \text{ ft.} \times 10 \text{ ft.} \times \frac{3}{4} \text{ cwt.} = 7{\cdot}5 \text{ D}$. If to this we add the total distributed load which the slab is required to carry, we get

$$W = 7{\cdot}5D + (12 \times 10 \times 1 \text{ cwt.}) = 7{\cdot}5D + 120.$$

According to Table XXII., No. 5, the value of C for concrete of the age and composition given, is 4·15. If we allow a factor of safety of about 4, we get a safe-load constant of (say) 1.

Formula IV. for beams *fixed* at the ends and *uniformly* loaded, is the one required for the present calculation, although, from the remarks already made, it will be understood that it probably under-estimates the strength of the fixed beams :—

$$W = 2C\frac{BD^2}{L}.$$

Transposing this, we get

$$D^2 = \frac{WL}{2CB}.$$

On substituting the data for the general terms, the equation stands thus :—

$$D^2 = \frac{(7{\cdot}5D + 120) \times 144}{2 \times 1 \times 120} = \frac{(7{\cdot}5D + 120) \times 3}{5}$$

$$D^2 = 4{\cdot}5D + 72$$

$$D^2 - 4{\cdot}5D = 72$$

By adding 5·0625 to each side of the equation we are enabled to reduce the equation to simpler terms :—

$$D^2 - 4{\cdot}5D + 5{\cdot}0625 = 72 + 5{\cdot}0625 = 77{\cdot}0625.$$

Find the square root of each side, and the result is

$$D - 2{\cdot}25 = 8{\cdot}78$$

and $D = 8{\cdot}7 + 2{\cdot}25 = 11$ inches.

The calculations may be simplified by taking an unit of width, instead of the actual width ; thus the weight upon (say) 1 inch or 1 foot may be taken and the thickness of this may be calculated, the result being the same as for the whole beam.

We shall see hereafter that if this slab were fixed along all its four edges instead of only along two, its strength would be doubled.

CHAPTER XVII.

COMPOUND BEAMS OF CONCRETE AND IRON.

Concrete compared with cast-iron—Addition of iron in tension—Two principles—Quantity of iron required—Example—Co-operation of iron and concrete—Slipping of iron ties—Mr. Hyatt's beams—Comparison of their tensile and compressive resistances—Calculations of their strength—Inaccuracy and danger of theoretical investigations—Tests for Mr. Hyatt and Mr. Edwards (Table XXIII.)—Deductions from the same.

Concrete compared with Cast Iron.—We have already explained that concrete alone is not a suitable material for resisting transverse stress on account of its feeble tenacity in comparison with its crushing strength. The same disadvantage was manifest in the case of cast iron, and the difficulty was met by making the area of the bottom flanges about six times as great as that of the top flanges. When all, however, was done that could be done, the result was unsatisfactory, and cast-iron girders were invariably looked upon with suspicion. They were readily abandoned in favour of rolled iron or steel girders when these were put upon the market.

Addition of Iron in Tension.—Concrete beams in the same way are rightly regarded with suspicion, but, unlike cast iron, the material does not readily lend itself to the formation of irregular sections. Experimenters have therefore turned their attention to the problem of devising some simple means of increasing the tenacity of concrete beams, and making it approximately equal to the compressive strength. A step in this direction would be to make the lower half of beams of a richer concrete than the upper half, but this would only go a very little way indeed towards meeting the difficulty. The method most usually

adopted has been that of embedding wrought iron bars or rods, which possess great tensile strength, in the lower half of the concrete, and the results have been satisfactory. The transverse strength of the compound beams greatly exceeds that of simple concrete beams, and instead of giving way suddenly and totally, the compound beams yield gradually and the collapse is only partial.

The first experiments in this direction were made, we believe, by Messrs. M. Allen & Son and Mr. Thaddeus Hyatt, the well-known inventor of semi-prism pavement-lights. The results of the latter's costly experiments were printed by him and privately circulated. As the book is not to be obtained by the general reader, Mr. Hyatt has very courteously permitted us to make extracts from it. Other experiments have more recently been made for Mr. F. G. Edwards, particulars of which will be found in *The Builder* for May 2, 1891. Before giving the details of these tests, it will be well to consider the theory of the combination of iron and concrete.

Two Principles.—Compound beams or slabs of iron and concrete may be constructed on two principles.

In the first place, the compressive strength of the concrete may be considered sufficient in itself, and iron is then added in such a position and quantity as will exactly suffice to give to the tension-half of the beam a tenacity equal to the compressive strength of the upper half.

On the other hand, it may be desired to increase not only the tensile but also the compressive strength of the beam. When we consider that good concrete has a crushing strength of only about 1 ton per sq. in., while wrought iron does not crush under less than about 16 tons per sq. in., we can see that the comparative weakness of the former can easily be eked out by the use of the latter material, but when this is done the quantity of iron in the lower half of the beam or slab should be proportionately increased, or the iron added to the upper half will be wasted. The use of symmetrical rolled iron joists in floors is therefore unscientific, unless the ironwork is designed to

carry the whole weight of the floor including the concrete; in which event, the concrete is considered merely as so much pugging, its strength being despised.

QUANTITY OF IRON REQUIRED.—In making any combination of iron and concrete, on the first principle just mentioned, the iron should exactly suffice to give to the tension half of the beam a tenacity equal to the compressive resistance of the upper half. In order to calculate accurately the quantity of iron required, it would be necessary to ascertain exactly the ratio existing between the tensile and the compressive strength of the concrete, but as this varies with almost every matrix and aggregate employed, only an approximation to the truth can be obtained. To show this variation, reference may be made to Table IV., page 30, where the tensile and compressive strengths of Roman cement are about as 1 to 6 or 7, and of Portland cement about as 1 to 8 or 9; further reference may then be made to Tables I. and XXI. (pages 20 and 183 respectively), and also to the section on the "compressive strength" of Portland cement (pp. 69—71).

Even in the case of Portland cement, the ratio is seen to vary greatly, but it is usually considered that the average ratio is about as 1 is to 10. Let us take these figures, and with their help try to obtain a compound beam of iron and concrete, in which the resistance to tension and compression shall be approximately equal.

Concrete composed of Portland cement and aggregate in the proportion of 1 to 4, may be taken to have a tensile strength of about 150 lbs. per sq. in., and a compressive strength of about 1,500 lbs. Wrought iron has a tensile strength of about 25 tons or 56,000 lbs. per sq. in. If we allow a factor of safety of 6 for the concrete, and of 5 for the wrought iron, we get the following working stresses:—

Concrete,	tension . . .	25 lbs. per sq. in.
	compression . .	250 " " " "
Wrought iron,	tension . . .	11,200 " " " "

EXAMPLE.—Figure 10 represents a concrete beam 6 ins. square, the neutral axis N being assumed to pass through

its centre of gravity ×. When the beam is loaded, the upper half will be in compression and the lower in tension. The stress in each case will be greatest at the greatest distance from the neutral axis, *i.e.*, along the lines AB and CD respectively. The stress along AB must not exceed 250 lbs. per sq. in., and that along CD 25 lbs. The stresses gradually diminish from the top and bottom surfaces of the beam to the neutral axis, where the tension and compression are each reduced to zero. The mean stress,

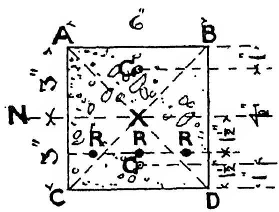


Fig. 10.—Section of Concrete Beam with Three Iron Tension-rods.

therefore, which can be put upon the upper half of the beam will be $\frac{250 + 0}{2} = 125$ lbs. per sq. in., and that on the lower half will be $\frac{25 + 0}{2} = 12{\cdot}5$ lbs.

In each case the resistance will be the mean stress × the area × one-third the depth of the beam, that being the distance of the centres of pressure* G of the upper and lower halves from the neutral axis. Therefore the resistance of the upper half of the beam will be

$$125 \times (6 \times 3) \times 2 = 4{,}500 \text{ inch-lbs.}$$

The resistance of the lower half will be

$$12{\cdot}5 \times (6 \times 3) \times 2 = 450 \text{ inch-lbs.}$$

* The centres of pressure of the two halves of the beam are at the centres of gravity GG of the two triangles AB× and CD×, which represent graphically the compressive and tensile stresses respectively, varying from the greatest stresses at the upper and lower surfaces to nothing at the neutral axis.

The additional resistance to be provided by the wrought iron is therefore 4,500 − 450, or 4,050 inch-lbs.

It is proposed to introduce the iron in the form of rods inserted in the concrete with their centres $1\frac{1}{2}$ ins. below the neutral axis of the beam. This allows them to be protected underneath by nearly an inch-and-a-half of concrete. The quantity of iron required to furnish the necessary resistance is $\frac{4050}{11,200 \times 1\cdot5} = \cdot25$ sq. in.

Three round rods of iron, each one-third of an inch in diameter, have an area somewhat in excess of this amount, viz., ·26 sq. in. These rods are shewn in the figure at RRR.

So far theory leads us, but in practice it is considered safer to neglect the strength of the concrete below the level of the iron rods, and in many instances indeed to neglect the tensile strength of the concrete altogether. In the latter event, the tensile strength of the iron rods would have to be made equal to the crushing strength of the concrete in the upper half of the beam. This is the more desirable because a severe fire may greatly lessen the strength of the underside of a concrete floor, even if it does not penetrate far enough to injure the iron embedded therein.

Co-operation of Iron and Concrete.—Again, it may be urged that the iron will be drawn through the concrete when the beam is loaded, unless the rods or bars are prevented from slipping. Certainly Mr. Hyatt's experiments in 1877 seemed to point to the truth of this contention, but more recent experiments, made by Mr. Kirkaldy on Mr. F. G. Edwards's patent iron and concrete beams, point the other way. These beams, it may be said, are simply beams of coke-breeze concrete having round iron rods embedded in the lower part, similar to the beam shown in fig. 10, and indeed similar in design to beams tested sixteen years ago by Mr. Hyatt. With reference to Mr. Edwards's beams, *The Builder* remarks,*—"It seems inherently improbable that the two materials would act together in resisting strains. The experiments of Tuesday last, how-

* *The Builder*, May 2, 1891.

ever, proved that the iron, in the form here applied, of an association of thin rods, would resist a very considerable strain and deflection without drawing; indeed, not one of the experiments showed any symptom of the iron drawing, and in one case it actually appeared that the iron rods had been perceptibly attenuated by the strain without losing their hold on the concrete."

SLIPPING OF IRON TIES.—In order to prevent the slipping of the iron ties, Mr. Hyatt tried several methods, including (1) riveting the ties (when these were round) through "heel-plates" at the ends of the beams, (2) turning up the ends of the ties when these were flat, (3) employing bars laid flat from which bolts with large washers at the top projected vertically into the upper half of the beam, and (4) employing flat bars laid edgeways and threading $\frac{1}{4}$-in. rods through them. The last method is the most effective, but in nearly every instance the bars were broken at the holes, through which the wires passed, before the concrete in the upper half of the beams yielded. This shows that the concrete can be trusted to take its share of the strain in a compound beam, namely, the compression.

Another method, which is adopted in an American system of concrete flooring known as the "Ransome" floor, consists in the use of *twisted* rods, which offer a better grip for the concrete than either round rods or flat bars do.

MR. HYATT'S TESTS.—Fig. 11 is a section of one of the beams containing cross-rods, tested by Mr. Hyatt, and it can be shown that the iron had not a tenacity equal to the compressive resistance of the concrete in the upper half of the beam. The beam was composed of Portland cement and crushed bricks (1 to 2), and was 2 or 3 months old when tested. Such concrete should have a compressive strength of at least 2,500 lbs. per sq. in. Seven bars of iron 4 in. × $\frac{1}{16}$ in. were embedded in the bottom half of the beam, and were connected and kept from slipping by $\frac{1}{4}$-in. rods 4 ins. apart. The resistance of the upper half of the beam would therefore be—

$$(12 \text{ in.} \times 4 \text{ in.} \times 1250 \text{ lbs.}) \times 2\tfrac{2}{3} \text{ in.} = 160{,}000 \text{ inch-lbs.}$$

The resistance of the iron bars (deducting $\frac{1}{4}$ in. in each case for the hole for the cross rods, and allowing a tenacity of 25 tons per sq. in. or 56,000 lbs.) would be—

$$7\ (3\tfrac{3}{4} \times \tfrac{1}{16} \times 28{,}000) \times 2\tfrac{2}{3} = 122{,}500 \text{ inch-lbs.*}$$

Even if we add the tenacity of the concrete in the lower half of the beam, we find that the combined resistance of the iron and the lower half of the concrete is nearly one-seventh less than the resistance of the upper half of the

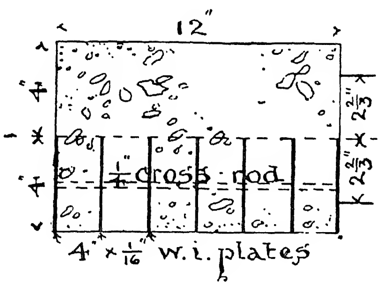


Fig. 11.—Section of Concrete Beam with Seven Iron Tension-plates.

concrete, and therefore that the beam would fail by the yielding of its tension-half. This, indeed, is what happened to this and four other beams of nearly similar section; in each case, Mr. Hyatt remarks, "Iron broken at rivet-holes." See Table XXIII., pp. 210—211.

Eight beams were made and tested, with a single bar of $2\frac{1}{2}'' \times \frac{1}{4}''$ wrought iron embedded in the concrete at a distance of 2 ins. from the underside, as shown in fig. 12. The bar was kept from slipping by means of $\frac{1}{2}$-in. bolts.

* In these calculations one half the ultimate tensile strength of the concrete and iron is taken for the reason explained on page 202.

extending upwards into the concrete and having large washers at the top. Two of the beams had 4 bolts, two had 7, two 10, and two 19, but the strength of the beams was not appreciably altered by altering the number of the bolts. In six out of the eight tests, the iron bars were broken at the bolt-holes.

These beams broke with about one-sixth less load than the beams shown in fig. 11, although the latter were only 8 in. deep while the former were 12 in. The reason is not far to seek. The iron in the former had an effective sectional area three or four times that in the latter, but,

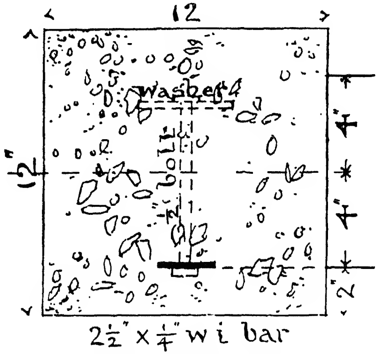


Fig. 12.—Section of Concrete Beam with Iron Tension-bar.

on the other hand, the iron in the larger beam was placed in a better position, namely, at one-sixth of the depth measured from the soffit upwards.

It may be interesting to work out the strength of these two beams according to an approximate formula. The beams were supported at the ends and loaded at the centre. The formula is based on the fact that the moment of resistance of a beam is equal to the bending moment, when the beam is not strained beyond the elastic limit. It is really not applicable to beams loaded to the breaking point, but it is sufficiently accurate for our present purpose.

CALCULATIONS OF STRENGTH.—*Example I.* (Fig. 11).—Find the breaking weight of a concrete beam, 12 in. wide, 8 in. deep, supported at the ends over a clear span of 60 in., loaded in the centre, the lower half of the beam having seven 4 in. $\times \frac{1}{16}$-in. wrought iron bars, as shown in the figure, with $\frac{1}{4}$-in. cross rods. The concrete must be composed of Portland cement and crushed brick (1 to 2).

As the tension half of the beam is (see p. 205) weaker than the other, we must base our calculations on it. The resistance of this is—

$$\begin{array}{lr} \text{(for the iron), } 7\ (3\tfrac{3}{4} \times \tfrac{1}{16}) \times 28{,}000^{*} = & 45{,}937 \\ \text{(for the concrete), } 11\tfrac{1}{2} \times 4 \times 125^{*} \ = & 5{,}750 \\ \hline \text{Total} \quad . \quad . \quad . & \underline{\underline{51{,}687}} \text{ inch-lbs.} \end{array}$$

The *moment of resistance* is 51,687 × two-thirds the depth of the beam, or $51{,}687 \times \frac{2}{3}$ of $8 = 275{,}664$ inch-lbs.

The bending moment of a beam loaded like the one under consideration is $\frac{WL}{4}$, and as the bending moment equals the moment of resistance, we get—

$$\frac{WL}{4} = 275{,}664, \text{ and } W = 275{,}664 \times \tfrac{4}{60} = 18{,}377 \text{ lbs.}$$

The beam actually broke with 23,884 lbs., and the dead weight of the beam, equivalent to a central load of 200 lbs., would bring the actual breaking weight to 24,084 lbs. This discrepancy may be due to the ultimate tensile strength of the iron having been under-estimated, or to the neutral axis adjusting itself to the unequal resistances, bringing a greater area under tension.

Example II. (Fig. 12).—Find the breaking weight of a concrete beam 12 in. wide, 12 in. deep, the lower half of the beam having a $2\frac{1}{2} \times \frac{1}{4}$-in. wrought-iron bar, as shown in the figure, with $\frac{1}{2}$-in upright bolts, supported and loaded as Example I.

* One-half the ultimate resistance for reasons already explained.

Proceeding as before, we find the resistance of the lower half of the section to be—

$$\begin{array}{lr} \text{(for the iron), } 2 \times \tfrac{1}{4} \times 56{,}000^{*} = & 28{,}000 \\ \text{(for the concrete), } 12 \times 6 \times 125 = & \underline{9{,}000} \\ \text{Total} \quad . \quad . \quad . & \underline{37{,}000} \text{ inch-lbs.} \end{array}$$

and
$$\frac{WL}{4} = 37{,}000 \times \tfrac{2}{3} \text{ of } 12$$
$$W = 37{,}000 \times 8 \times \tfrac{4}{60} = 19{,}733 \text{ lbs.}$$

The beams actually broke with loads ranging from 15,938 to 21,592 lbs.

It has been recommended that the concrete below the iron, in such beams as the last, should be omitted from the calculations of strength, and should be considered as dead-weight only. This method would give a smaller breaking-weight, if the beam were taken as only 10 in. deep instead of 12 in., and the neutral axis were assumed to pass through the centre of the upper 10 in. of the beam. W would then be found to be 15,777 lbs.

INACCURACY AND DANGER OF THEORETICAL INVESTIGATIONS.—But the whole question of the strength of compound beams is fraught with difficulties, and at the best, only an approximate estimate of their breaking-weight can be made. As a large factor of safety (certainly not less than 5 or 6) must be allowed, the calculations are perhaps near enough for practical purposes, but too much reliance must not be placed upon them.

Some recent words of Sir Benjamin Baker may well be quoted in this connection. In a discussion at the *Institution of Civil Engineers* in November, 1892, he spoke to the following effect:—"Bearing upon the general question of the value of theoretical investigations of strength, in cases

* In the preceding example the iron extended from the neutral axis to the lower edge of the beam, and the stress on the iron was taken at one-half the ultimate stress; in this, the iron is placed horizontally, and the ultimate stress is taken, although this is rather over-estimating the strength of the beam.

such as a flat concrete invert, as compared with direct practical experience, he might say that several cases recently had made him a little nervous as to whether the results of the high technical training of the present day with many young engineers did not lead to a dangerous confidence in theoretical deductions and the use of formulas. No one could charge him with contempt of theory; but cases had been brought under his notice rather frequently of late showing too great confidence on the part of young engineers in theoretical deductions, in preference to going to the same extent as their predecessors had been in the habit of doing to previous examples, in order to see what was the right proportion to adopt in a particular work." *

Tests for Mr. Hyatt and Mr. Edwards.—The following table gives the results of the tests carried out by Mr. Kirkaldy, in 1877, for Mr. Thaddeus Hyatt, and in 1891, for Mr. F. G. Edwards, the former being numbered 1 to 11 and the latter 12 to 16. The figures for Mr. Hyatt's beams are taken from his book, "Experiments with Portland-Cement Concrete combined with Iron," and those for Mr. Edwards's beams from an article in *The Builder* for May 2, 1891. In the column headed "Ratio of Iron to Concrete," the calculation is based on the effective sectional area of the iron, and the area of the concrete exclusive of that portion which lies below the underside of the iron; thus, in Nos. 8 to 11, the wrought-iron bar in each measures $2\frac{1}{2}$ in. × $\frac{1}{4}$ in., but as half-inch holes are bored through it to receive the upright bolts, the effective sectional area of the bar is only 2 in. × $\frac{1}{4}$ in., that is to say, ·5 sq. in.; in the same beams, the extreme depth of the concrete is 12 in., but as 2 in. of this lie below the iron bar, this portion is omitted from the calculations, the sectional area being taken therefore as 12 in. × 10 in., that is to say, 120 sq. in.

Deductions. Several instructive lessons may be learnt from these experiments.

* *Proceedings of the Inst. C. E.*, vol. cxi. (1892-3, part i.)

TABLE XXIII.—TRANSVERSE STRENGTH OF COMBINED CONCRETE-AND-IRON BEAMS (*a*), SUPPORTED AT THE ENDS, AND LOADED AT THE CENTRE.

Number.	Composition (*a*). Portland Cement.	Composition (*a*). Aggregate.	Age.	Breadth.	Depth.	Clear Span.	No. of Tests.	Average Breaking Weight.	One-half weight of beam between supports (*b*).	Total Central Load.	Constant (*c*).	Ratio of Iron to Concrete.	Remarks.
				in.	in.	in.		cwt.	cwt.				
1	1	2 crushed brick	"2 or 3 months"	12	8	60	1	13·25	1·83	15·08	1·76	0 : 1	Concrete only.
2	1	,,	,,	12	8(*d*)	60	1	82·8	1·84	84·64	12·95	1 : 150	Ties not broken, but pulled through.
3	1	,,	,,	12	8	60	1	224·53	2·03	226·56	26·55	1 : 38	Iron broken at holes for cross-rods (*e*).
4	1	,,	,,	12	8	60	1	230·96	2·00	232·96	27·3	1 : 46	,, ,,
5	1	,,	,,	12	8	60	1	213·25	1·97	215·22	25·22	1 : 58	,, ,,
6	1	,,	,,	12	8	60	1	189·48	1·94	191·42	22·43	1 : 80	,, ,,
7	1	,,	,,	12	8	60	1	146·58	1·91	148·49	17·4	1 : 125	,, ,,
8	1	,,	,,	12	12(*f*)	60	2	159·25	2·84	162·09	12·15	1 : 240	In one beam, concrete crushed and tie drawn out; in the other, tie broken at bolt hole.
9	1	,,	,,	12	12(*f*)	60	2	157·11	2·85	159·96	12	1 : 240	Ties broken at bolt hole.
10	1	,,	,,	12	12(*f*)	60	2	172·35	2·86	175·21	13·14	1 : 240	,, ,,
11	1	,,	,,	12	12(*f*)	60	2	180·61	2·89	183·50	13·76	1 : 240	As No. 8 above.
12	1	1 coke breeze ($\frac{1}{2}$ in.)	7 days	3	7(*g*)	120	1	25·66	·57	26·23	37·25	1 : 33	Concrete crushed at top.
13	1	1 ,, ,, ($\frac{1}{4}$ in.)	21 ,,	3	5(*h*)	72	2	19·59	·17	19·76	33·61	1 : 49	Lower flanges cracked.
14	1	1 ,, ,, ($\frac{1}{2}$ in.)	7 ,,	3	5(*h*)	72	2	22·33	·24	22·57	38·39	1 : 41	Cracked at bottom and crushed at top simultaneously.
15	1	1 ,, ,, ($\frac{1}{2}$ in.)	7 ,,	3	5	72	1	3·85	·22	4·07	5·86	0 : 1	Broke suddenly right through.
16	Exceptionally good fir joist		...	3	5	72	1	54·52	·09	54·61	72·62	...	...

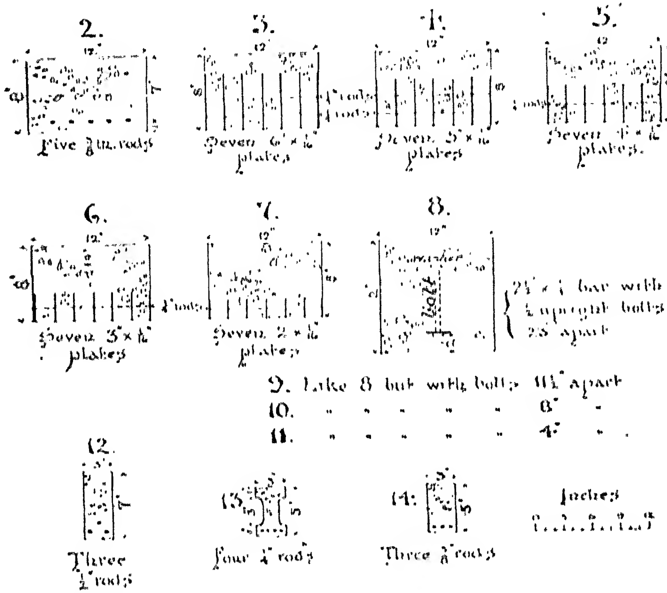


Fig. 13. Sections of Compound Beams of Concrete and Iron, mentioned in Table XXIII.

Notes on Table XXIII.

(*a*) For the sections of the various beams showing the arrangement of the iron bars, rods, &c., see the illustrations in Figure 13, which are numbered to correspond with the numbers in the table.

(*b*) See note * to Table XXII., p. 191.

(*c*) For use in the formula $W = \frac{2}{3} C \frac{BD^2}{L}$.

(*d*) The concrete below the iron rods is omitted from the calculations of strength, the depth of the beam being reckoned 7 in.; if the depth of the beam were taken as 8 in., the constant would appear 9·92 instead of 12·95.

(*e*) The eighteen ¼ in. cross-rods are to the longitudinal section of the concrete as 1 is to 640.

(*f*) The concrete below the iron bar is omitted from the calculations of strength, the depth of the beam being reckoned 10 in.

(*g*) The concrete below the iron rods is omitted as before, the depth of the beam being reckoned 6·5 in.

(*h*) The concrete below the iron rods is omitted as before, the depth of the beam being reckoned 4·6 in.

1. Compare the strength of the simple brick-concrete beam No. 1 with the strength of similar concrete beams Nos. 2 to 11 in which wrought iron ties had been imbedded; also compare the strength of the simple beam of coke-breeze concrete, No. 15, with the three preceding beams, Nos. 12 to 14, containing wrought iron rods. The immense gain of strength accruing from the use of such a small quantity of iron is surprising. It must, however, be said that the ironless beam, No. 1, was weaker than might have been expected (see Table XXII., pp. 190—1).

2. Notice that, with two exceptions, the thirteen beams included in Nos. 3 to 11 yielded by the breaking of the iron bars; in only two instances did the beams yield by the crushing of the concrete. This shows that sufficient iron had not been used, or had not been used in the proper position.

3. Beam No. 3 contained more iron in proportion than any other of Mr. Hyatt's beams, but it had not the greatest strength. The reason is that the iron was not placed in the most advantageous position, one-third of it extending above the middle of the beam, and therefore adding little or nothing to the tensile strength. Beam No. 5, which contained one-third less iron, was only 5 per cent. weaker. This shows that iron above the medial line of a beam is of little use, unless an increase, commensurate in strength, is made in the iron in the lower half.

4. As might have been predicated, the most advantageous position for the iron tension rods is shown by experiments 12 to 14, to be near the bottom of the beam. The eight beams Nos. 8 to 11 contained much too little iron, and therefore give rather low constants, although the iron was placed in a good position; there would be less danger of the protecting layer of concrete underneath peeling off, if the iron bars were placed on edge instead of flat.

5. With good coke-breeze concrete, the ratio of iron tie-rods to the concrete should apparently be not less than 1 in 40, when the rods are in a proper position. This may be assumed from the facts that beam No. 14, containing

$\frac{1}{41}$ part of iron, cracked at the bottom and crushed at the top simultaneously, and that beam No. 12, containing $\frac{1}{33}$ part of iron, crushed at the top, but did not fail at the bottom. As, however, these beams were tested when the concrete was only seven days old, and therefore less than one-half its ultimate strength, we may consider that wrought iron ties, properly placed in concrete beams, should have a sectional area about one-twentieth of that of the concrete, neglecting that part of the concrete which lies below the iron. The proportion will, however, differ, not only according to the position of the iron, but also according to the crushing strength of the concrete (see Table XVI., p. 127; Table XXI., p. 183, &c.).

6. The result of the test on beam No. 2, in which five $\frac{3}{8}$-in. round wrought iron rods were used, and the results of other tests made for Mr. Hyatt, but not given in the table, show that there is a danger of iron ties being drawn through the concrete, unless they are held by being secured through plates at the ends, or in some other way. None of the beams, however, tested for Mr. Edwards, yielded in this manner, although the rods were held simply by the adhesion of the concrete. It is said that cement adheres more firmly to iron when this is left with its natural surface, and not treated by any anti-rust process; and if this be so, iron rods embedded in concrete should not be coated in any way. As they are surrounded entirely with the concrete, there will be no danger of future rusting, unless the concrete is of a porous character.

7. Test No. 16 was carried out on a "fir joist of exceptionally good timber." This had a strength nearly double that of the best concrete and iron beams, but as the latter were only seven days old, and the former was an "exceptionally good" specimen, the disparity in their strength need not lead to a wholesale condemnation of the concrete and iron. *On the contrary, it shows conclusively that solid floors of concrete, with iron in the lower part only, can be constructed which will be stronger than an ordinary joisted floor of the same thickness.* For each wooden joist has to carry

a floor-surface three or four times its own width, whereas the concrete floor is solid and may therefore be, per unit, one-third or one-fourth the strength of a corresponding width of joist. In addition to this, the concrete floor may have the advantage of being fixed along all its sides instead of only along two, as is the case with joisted floors; and this is no mean advantage, for a square slab is 100 per cent. stronger when all its edges are fixed, than when only two opposite edges are fixed.

Recent Examples.—More recently wrought iron and steel have been used in concrete in a variety of ways, such as the twisted rods of the Ransome system, and the steel network of the Expanded Metal Company's system. The general term "Armoured concrete" is now applied to these and other methods of construction in which concrete and iron are used in combination. Armoured concrete of various kinds is now used for beams in floors, roofs, &c. but it will be more convenient to give a general account of this important subject in a separate chapter (chapter XXVI). In passing it may be said that in nearly all these systems the concrete itself is richer in cement and contains a finer aggregate than is customary in ordinary work.

CHAPTER XVIII.

FOUNDATIONS.

London C. C. regulations, and observations thereon—Thickness of ordinary concrete foundations—Bearing power of grounds—Nature of stress—Calculation of thickness, &c., of foundations of concrete and brick—Foundation entirely of concrete—Concrete and stone—Concrete and steel—Concrete and piles—Foundation-layer—Arches in foundations—Piers and arches—Ingredients in lime concrete (Table XXIV.)—Caissons—Springs of water—Grouting—Machine-beds, &c.—Concrete in water.

EXCEPT in those districts where there is an abundant supply of rag-stone footings, concrete is universally used in England for foundations, perhaps alone, or in conjunction with piles, steel rails, &c.

LONDON COUNTY COUNCIL REGULATIONS.—The regulations of the London County Council respecting foundations are as follows :—

"The foundations of the walls of every house or building shall be formed of a bed of good concrete, not less than nine inches thick, and projecting at least four inches on each side of the lowest course of footings of such walls. If the site be upon a natural bed of gravel, concrete may be omitted from the foundations of the walls, with the approval of the District Surveyor.

"The concrete must be composed of clean gravel, broken hard brick, properly burnt ballast, or other hard material to be approved by the District Surveyor, well mixed with freshly-burned lime or cement in the proportions of one of lime to six, and one of cement to eight of the other material."

These regulations are open to several grave objections.

In the first place, it is matter for surprise that, while the thickness of walls is carefully defined according to their height, length, &c., the thickness of the foundations, on which the stability of the walls primarily depends, is not prescribed more particularly than "not less than 9 in. thick."

Then, again, why should it be necessary to use brick footings at all, when we know that Portland-cement concrete (1 to 8) is nearly four times as strong as brickwork set in cement mortar (1 to 1)?* The thickness of the concrete might be increased, and the wall built upon it without any brick footings; a saving in the total thickness of the foundations might thus be effected without loss of strength.

Nothing is said as to whether the sand and coarse material are to be measured separately or not, and this, as we have shown, is a matter greatly affecting the strength of concrete. The quality of the cement is not even mentioned.

And lastly, concrete may be of nearly any kind of lime, however feebly hydraulic, in the proportion of 1 lime to 6 aggregate; while, if the very best Portland cement be used, no more than eight parts of aggregate can be mixed with it, and yet the latter might be eight or ten times the strength of the former. Surely the framers of these regulations could not have known the results of Mr. Grant's experiments on the strength of various kinds of concrete.†

The first and chief objection to these regulations is one which has not escaped the notice of architects. In November, 1891, "Suggestions ‡ for a draft bill for the codification and amendment of the metropolitan building acts" were adopted by the Council of the *Royal Institute of British Architects*, and one of the suggestions refers to this matter. In the section (XVII.) on "Foundations and Sites of Buildings," the following paragraph occurs:—

"*The foundations of the walls of every house or building*

* John Grant.

† See Table XXI. p. 183, *et seq.*

‡ *Transactions R. I. B. A.*, vol. viii., New Series (1892).

shall be formed of a bed of good concrete, or other material approved by the Council, of the thickness shown in the Schedule No.   attached to this Act, arranged according to the heights of the walls of (*a*) domestic buildings, and (*b*) warehouses, *and projecting at least four inches on each side of the lowest course of the footings of such walls. If the site be upon a natural bed of* solid *gravel* or chalk of not less than three feet in thickness, *concrete may be omitted from the foundations of the walls with the approval of the District Surveyor.*" *

Thickness of ordinary Concrete Foundations.—The schedule referred to in the foregoing paragraph does not appear in the suggestions, for the simple reason apparently that it has not been prepared. Its preparation, indeed, would involve considerable labour, as different kinds of ground would require different thicknesses and widths of concrete according to their bearing power, and in many cases, concrete might even be omitted altogether.

The minimum thickness of concrete required by the London County Council is, as we have said, 9 in., but it is seldom that, in good work on ordinary ground, so small a thickness is used except for the thinnest internal walls. The foundations for external walls are seldom thinner than the walls they carry, and, as a rule, range from this up to about twice the thickness of the walls. The concrete under some of the walls of Street's Law Courts was 7 ft. thick, and that under the walls of the Great Hall was 10 ft. thick.

The thickness of concrete foundations is a subject which has received little attention from writers. It is undoubtedly fraught with difficulties, as in every case there are "unknown quantities," which give an element of uncertainty to the calculations. For this reason it is, perhaps, that architects are usually content to guess at the thickness required.

Bearing Power of Grounds.—The first "unknown quantity" with which we have to deal, is the bearing power

* The words in italics have been retained from the existing regulations.

of the ground itself. This, of course, may vary from nearly zero for bog to several hundred tons per square foot for solid granite. In founding on bogs or very soft ground, piles or caissons of concrete or some other contrivance must be adopted. But on ordinary ground concrete itself is sufficient.

The safe bearing power of various kinds of ground is, roughly, as follows, in cwts. per square foot:—Alluvial soil or quicksand, 10 to 15; soft clay (near surface), 10 to 15; moist clay, 20 to 30; compact clay, nearly dry, 40 to 50; dry compact clay of considerable thickness, 60 to 100; loose sand, 20 to 30; compact sand, 40 to 60; ditto, prevented from spreading, 100 to 150; gravel and sand, 40 to 60; ditto, compact, dry, and prevented from spreading, 80 to 120. The bearing power of most solid rocks is far in excess of any weight which in ordinary buildings can be put upon them, but great care must be exercised on rocky sites in bridging over soft dykes or fissures with concrete, as otherwise unequal settling must occur. But of this, more anon.

Nature of Stress.—It is often thought that the stress which is put upon foundations is simply a compressive one, but this is not the case. There is more or less of a transverse stress, caused by the weight of the wall acting upon the central portion of the foundation and tending to crack it longitudinally. To minimise this stress, the lower portion of the wall is spread out gradually almost to the breadth of the foundation proper.

But the amount of the transverse stress varies according to the supporting power of the ground and the width of the foundation (the latter, however, being modified by the spread of the lower part of the wall). If the concrete be laid on solid rock, there is no transverse stress; in such a position, concrete is not needed, for the chief office of concrete is to distribute the weight of the wall over such an area of ground that little or no settlement may occur. The firmer the ground the less may the width and thickness of the concrete be.

Calculation of Thickness, &c.—Figure 14 shows the foundations of an 18-in. wall with the brick footings and concrete of the widths required by the London County Council regulations. The method of calculating the thickness of the concrete is as follows. In the first place, ascertain the total weight of the wall, floors, and roof acting upon the foundation. Due allowance should be made for the moment of the wind-pressure, when the building is in an exposed situation; in ordinary situations, the wind pressure may be omitted from the calculations, and a somewhat larger factor of safety adopted.

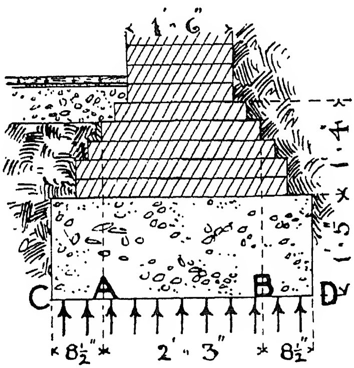


Fig. 14.—Ordinary Foundations of Concrete and Brick.

In the case before us, the total downward pressure upon the foundations is assumed to be 132 cwt. per lineal foot.

The second point to be ascertained is the nature of the ground. Suppose that in this case it is somewhat moist clay with a safe bearing power of about 36 cwt. per square foot.

Divide the total downward pressure upon the foundation, namely, 132 cwt. per lineal foot, by the safe bearing-power of the ground, namely, 36 cwt. per square foot, and the quotient will be the width of the concrete—3 ft. 8 in., as shown in the figure.

The second "unknown quantity" now thrusts itself upon our notice: to what extent is the weight of the wall distributed by the brick footings? Probably the outermost half-brick at each side bears little or none of the weight, but so much depends on the bricks, the bond, and the mortar, that no definite rule can be laid down. Assuming such, however, to be true in this case, we have the weight of the wall, &c., distributed over the central 27 in. of the concrete, as shown at A B.

As action is equal and opposite to reaction, the upward thrust of the ground, shown by the arrows under the concrete, is as the weight upon it—namely, 36 cwt. per square foot. The concrete between A and B will be subject to simple compressive stress, but the parts A C and B D are inverted cantilevers, uniformly loaded, and fixed at A and B respectively. Perhaps the calculations will be more easily followed if the figure be turned upside down. Formula VII. in the preceding chapter gives the breaking weight of uniformly-loaded cantilevers:—$W = \frac{1}{3} C \frac{B D^2}{L}$.

Transposing this, we get:—$D^2 = \frac{3 W L}{C B}$.

In this example, $L = 8{\cdot}5$ in., $B = 12$ in., $W = \frac{8{\cdot}5}{12} \times 36 = 25{\cdot}5$ cwt., and $C = 1{\cdot}5$ for concrete composed of 1 Portland cement, 2 sand, and 6 broken stone.*

Substituting these values for the letters on the right-hand side of the equation we get—

$$D^2 = \frac{3 \times 25{\cdot}5 \times 8{\cdot}5}{1{\cdot}5 \times 12} = 36{\cdot}13 \text{ in.}$$

From this we might proceed to say that $D = 6{\cdot}01$ in. As, however, no factor of safety has yet been allowed, this thickness of concrete would not suffice; in fact, this is the thickness at which fracture would just occur. It will not be wise to allow a smaller factor of safety than 6, and in

* No. 18, Table XXII. page 190.

many cases it will be better to use 7 or 8. If, however, we multiply the depth obtained in the equation above, namely, 6·01 in., by the factor of safety, we obtain a result far in excess of what is required, for the strength of beams increases as the *square* of the depth. A beam 24 in. deep is 4 times as strong as one 12 in. deep, and 16 times as strong as one 6 in. deep. Therefore, the thickness found by the equation should be multiplied only by the square root of the factor of safety. Or, the value of D^2 may be multiplied by the factor of safety, and the square root of the product may then be found. This will usually be the simpler method to adopt.

Reverting to the example, we have—

$$D^2 = 36{\cdot}13.$$

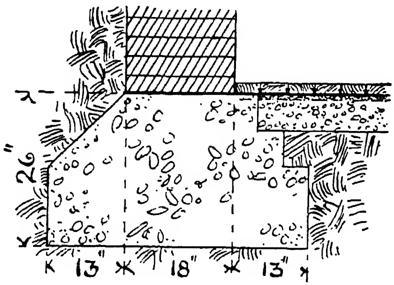


Fig. 15.—Foundation wholly of Concrete.

Allowing a factor of safety of 8 we get—

$$D^2 = 36{\cdot}13 \times 8 = 289{\cdot}04 \text{ in.}$$
$$D = \sqrt{289{\cdot}04} = 17 \text{ in.}$$

This is the thickness shown in the figure.

Foundations entirely of Concrete.—Figure 15 shows two methods of forming the foundations of the foregoing wall entirely of concrete, the brick footings being omitted.

In this case, the length of each cantilever is 13 in., and $W = \frac{13}{12} \times 36 = 39$ cwt. Proceeding as before—

$$D^2 = \frac{3 \times 39 \times 13}{1 \cdot 5 \times 12} = 84 \cdot 5.$$

Multiply by the factor of safety, 8, as before.

$$D^2 = 84 \cdot 5 \times 8 = 676,$$

and $$D = 26 \text{ in.}$$

This is the thickness shown in the figure. It is 6 in. less than the thickness of the combined brick and concrete foundations shown in Fig. 14.

Instead of multiplying by the factor of safety as above, the constant may be *divided* by the factor of safety, and if the quotient be used in the formula, the result of the calculations will be the safe thickness or strength as the case may be.

The sides of the concrete could be sloped or stepped, as in Fig. 15, without in any way detracting from its strength. The slope, however, would be more easily formed, and would probably give the best results as sharp angles are a source of weakness. The slopes and set-offs would have to be formed with boards roughly fixed in position, and removed when the concrete had set.

Certainly the foundation entirely of concrete would be more economical than that of concrete and brick, strength for strength. The London County Council regulations, however, insist on the brick footings, although in many cases, owing to bad bond, soft bricks, and mud-like mortar, the brick footings are of extremely doubtful service.

Concrete and Stone.—Where strong ragstone slabs can be economically obtained, one or two courses are frequently laid on the concrete instead of brick footings. They have the advantage over brickwork, of distributing the weight more surely, and in calculating the thickness of the concrete the length of the cantilever may be taken to be the

projection of the concrete with an inch or two added to allow for the irregular edges of the slabs.

In America, where buildings of extravagant height are often erected, great attention is of necessity bestowed upon the foundations. In the case of the offices of the *New York Tribune*, a building measuring 150 ft. high from the footpath to the eaves, the substructure consisted of a bed of concrete the top of which was 25 ft. below the footpath. The concrete rested on a good bed of firm red beach sand, and was composed of 1 part Portland cement, 3 parts sand, 4 parts clean white gravel, and 5 parts broken stone, mixed wet and well rammed in 6-in. layers to a total thickness of 18 in. This mixture (1 to 12) was found strong enough, but it must be confessed that little or no transverse stress was applied to it, for immediately over it was laid a course of immense granite slabs 9 ft. wide and 16 in. thick, and on this the foundation-walls, 6 ft. 8 in. thick, were built of fire-brick laid in Portland cement, with granite bond-stones 10 in. in thickness at intervals of 3 ft. up to the level of the basement floor.

CONCRETE AND STEEL.—In Chicago the practice of bedding steel rails in concrete for foundations has been frequently adopted. It appears from Mr. A. Arthur Cox's report* that in that city "the subsoil is composed of a black loamy clay, which, on the surface, is tolerably firm, but a few feet below, and in some parts to a depth of 12 ft. to 15 ft., is quite unfavourable to building operations." Where cellars are required the footings must be as shallow as possible, so as not to get into or near the soft substratum. Fig. 16 shows the foundation of one-half of a pier in the *Rookery* Office Building, Chicago. This building is eleven stories high, each story measuring about 12 ft. A layer of concrete 18 in. thick is first deposited, and on it are laid four courses of steel rails $4\frac{1}{2}$ in. deep, the first transversely and the next longitudinally, and so on; these are "spaced evenly at small intervals," the spaces being thoroughly

* See "A Tour in the United States," by A. Arthur Cox, holder of the Godwin Bursary, *Transactions of the R. I. B. A.*, 1891.

filled with cement concrete. On the top of the rails is laid a course of hard stone 6 in. thick; above this the pier is built of brick. The total thickness of the foundations is only 3 ft. 6 in., while the thickness up to the top of the uppermost set-off is only 2 ft. $7\frac{1}{2}$ in.

As the steel is entirely surrounded with good concrete, there is no reason to fear that it will gradually corrode. The ends of the rails, shown in the figure, might, however, be advantageously protected by covering them with concrete, the upper surface of which might be made to slope from the upper edge of the concrete layer to the top of the whole foundations. For the Ransome system see page 236.

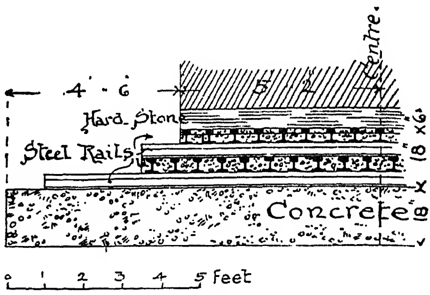


Fig. 16.—Foundation of Concrete and Steel Rails.

Steel in foundations has also been used in England. A recent example is the "Eiffel" tower now being erected at Blackpool from the designs of Messrs. Maxwell & Tuke. The four great legs of the tower rest on concrete blocks, each 34 ft. square and 12 ft. thick, in which 12 in. × 6 in. steel girders are embedded.

In Chicago, it may be added, there seems to have been recently a revulsion of feeling in favour of timber piles, driven right through the soft bed into the hard stratum below.

Concrete and Piles.—Timber piles are often used for foundations in soft ground, where it is not considered

desirable or possible to excavate the ground to a solid substratum. They are usually of ordinary red deal (preferably of whole timber), creosoted and shod with cast or wrought iron shoes. Other kinds of wood, such as pitch-pine, oak, elm, &c., are sometimes employed. Piles are used of various-sized timber according to the work they have to perform—the weight to be borne, the length of the pile, and the nature of the ground. They are seldom less than 6 in. in diameter (or 6 in. square), or more than 14 in. square. The driving of the piles is usually effected by means of a "pile-engine," which consists of a tall frame-work with upright guides, between which a weight (technically, a "monkey") is hoisted and falls, when released by a trigger, upon the head of the pile beneath. The weight of the monkey is important, as a very light one may not drive the pile deep enough, or, if a great fall be allowed in driving, may split the pile. The weight may vary from about 2 or 3 cwt. for 6 in. piles to about 15 cwt. for 12 in. piles.

The supporting power of piles is difficult to calculate with any degree of accuracy. The subject is foreign to our purpose, but the well-known simple formula of Major Sanders may be given :—

$$\text{Safe load in cwt.} = \frac{\text{WH}}{8\text{D}},$$

where W = weight of monkey in cwt.,
H = height of fall of monkey in inches,
D = distance driven by last blow, in inches.

Thus, a pile, which sinks $\frac{1}{4}$ in. under a weight of 9 cwt. falling 60 in., may be expected to bear a safe load of $\left(\frac{9 \times 60}{8 \times \cdot 25} = \right)$ 270 cwt or $13\frac{1}{2}$ tons. This of course is a rough-and-ready formula, but it is applicable for ordinary work, where the pile is supported throughout its length.

Mr. D. K. Clark considers that a 12 in. square pile, 20 ft. in the ground and supported throughout that length so as

to be prevented from bending, will bear 9 tons in ooze or muddy sand, 12 tons in moderately compact clay, 25 tons in hard clay, and 80 tons if it reaches hard gravel.

At one time, before concrete had come much into use, it was the custom to bind the heads of the piles together by means of longitudinal and transverse balks of timber, and

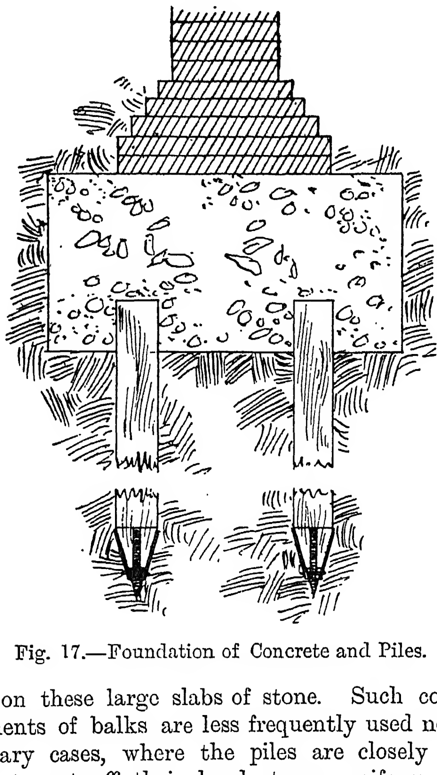


Fig. 17.—Foundation of Concrete and Piles.

to lay upon these large slabs of stone. Such complicated arrangements of balks are less frequently used now-a-days. In ordinary cases, where the piles are closely set, it is sufficient to cut off their heads to an uniform level, and after excavating the ground between them to a depth of one foot or more (according to the size of the piles, &c.), to fill the trench around and above the piles with concrete

well rammed. This is illustrated in Fig. 17, where two rows of 7-inch piles are shown under an ordinary concrete and brick foundation. For heavy walls, however, and where the piles are not closely set, the heads of the piles must be united by strong timbers.

Cast or wrought iron piles are frequently used in engineering works, but not often by architects.

Concrete Foundation-Layer.—Sometimes the whole site of a building is covered with concrete. The least allowable thickness is 9 in., if the brick footings of the walls are to be built directly upon the concrete; but a thickness of 12 in. is more usual, even for the smallest buildings, and a thick-

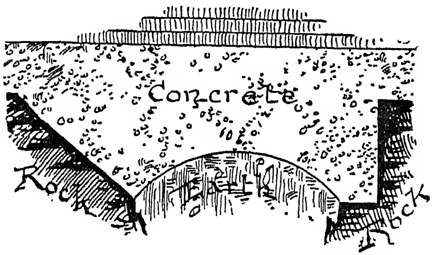


Fig. 18.—Concrete Arch over Soft Dyke.

ness of 18 in. and upwards is adopted for larger structures, according to the weight of the building and nature of the ground.

Frequently, however, an additional thickness of concrete is put under the walls. When the concrete under the walls is kept quite independent of the concrete layer which is spread over the site, the layer is usually only 6 in. thick, and the top of it is finished level with the top of the concrete foundation, or with the top of the brick footings, if the appearance of these in the basement would be objectionable. Such a layer is really not part of the foundation.

Arches.—The application of concrete to foundations is not, however, confined to simple slabs. In rocky ground,

concrete may be used in the form of an arch or lintel to span a soft dyke, abutting at each end on the solid rock, which may be splayed or benched to receive it, as in Fig. 18. The thickness of the concrete must be regulated by the weight the arch has to carry. The earth under the concrete can be brought to an arched form and rammed, so that no boards or centres will be required.

Inverted arches between piers may be very conveniently and economically formed in concrete instead of brickwork.

Piers and Arches.—Where the site of a building consists of a considerable depth of "made" ground, or is naturally soft but with an underlying firm layer, it will often prove economical to erect concrete piers, and to form concrete arches over them, instead of laying a continuous foundation. The ground under the piers should be very firm, or disaster may follow. On steep ground the system of piers and arches is often advantageous. Fig. 19 illustrates the method adopted (1882—4) in the foundations of the east wing of the Army Headquarters at Simla, India.* The ordinary foundations in these buildings consisted of a series of concrete piers to carry iron columns, and with cross-footings between to carry the cross walls, but where the excavation, in order to get a good bottom, was carried more than 10 ft. deep, "groined arches" were thrown from pier to pier to carry the cross walls.

The concrete for the whole of the buildings consisted of *hydraulic lime*, ground on the building-site and used quite fresh and without slaking or wet-grinding; *surkhi* (pounded bricks), ground on the site and screened through a sieve of 132 meshes to the inch (superficial) for fine work, and through $\frac{1}{8}$-in. and $\frac{3}{16}$-in. bar screens for ordinary work; and *limestone*, broken by hand to pass a 1-in. ring. The lime and surkhi were mixed dry in the proportion of 1 to 2; 5 cubic feet of ground lime + 10 cubic feet of surkhi, mixed dry, made 14 cubic feet of "dry mortar." This was

* See paper by Mr. Walter Smith, A.M.Inst.C.E., in the *Proceedings of the Inst. C. E.*, vol. lxxxiii. (1885-6), part i.

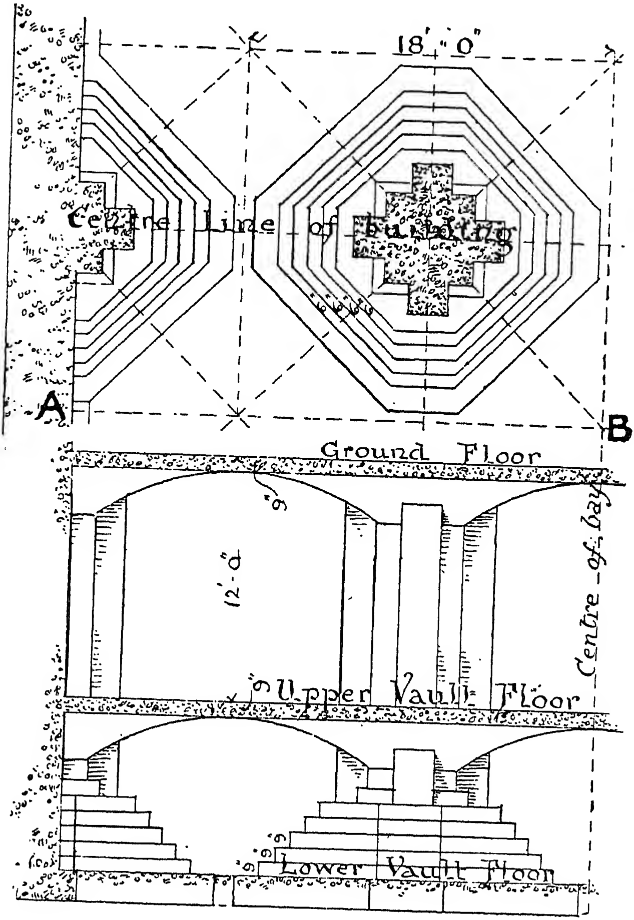


Fig. 19.—Plan and Section (on line A B), of the Foundations of the Army Headquarters, Simla.

mixed with the aggregate in the proportion of 42 to 100 for ordinary foundations, and 45 to 100 for walls and arched vaulting. For ordinary foundations, therefore, the concrete consisted of 1 part lime, 2 parts surkhi, and 6·6 parts broken stone, a rather poorer concrete than would be allowed by the London County Council.

The following table shows the material used to make 100 cubic feet of rammed concrete of each kind :—

Table XXIV.—Bulk of Ingredients in Lime Concrete.

	Ordinary Foundations.	Walls and Arched Vaulting.
	cub. ft.	cub. ft.
Lime	17·5	19
Surkhi	35	38
Dry Mortar	49	53
Stone Ballast	117	117
Rammed Concrete	100	100

The concrete in the foundations was deposited in 3-in. layers, and "rammed until the moisture exuded at the top, and the blows of the rammer caused no further yielding in the mass." Stones and boulders were imbedded in the concrete, and in this way a saving of about 6 per cent. was effected. The outline of each foundation was marked by rough stone walling lined with planks, and as each course was completed and sufficiently set (usually in three days), the planks were removed and the space between the piers was filled with earth well rammed.

Successive courses were laid in this manner until the springing of the arches was reached. Then earth was heaped up, well rammed, moulded by templates to the shape required for the groining, and plastered first with cow-dung and afterwards with lime-plaster. Concrete was then deposited and rammed up to the floor-level, "each vaulted arch being completed to its full thickness before

the next was commenced. At a later period the earth-centres were removed, when the groins were found to be clearly defined."

Underpinning.—Concrete is frequently used for underpinning walls, the foundations of which have yielded or which have to be taken to a greater depth for better basement accommodation. The operation can be carried out in almost any length at a time if the wall be supported on needles and posts, or in short lengths of four or five feet at a time without needles. Concrete for such work should be of richer quality than for ordinary foundations, as the greatest weight which it has to carry, will come upon it before it has had much time to harden. A good mixture would be 1 part quick-setting Portland cement, 1 part coarse clean sand, and from 4 to 6 parts washed aggregate of irregular shape and size free from sand. The usual method is to deposit a bed of concrete of suitable width and thickness and of convenient length, and upon this to build a new wall in brick or stone bedded in cement mortar (about 1 cement to 2 sand), up to the old wall, and to pin the uppermost joint with slate or iron wedges. The new work can be strengthened by grouting, and the uppermost joint can be effectually filled by taking out some of the old bricks above the joint every few feet, and pouring thick neat cement grout into the middle of the wall. Unless needles are used, underpinning should not be carried out rapidly, or the weight may be put on the concrete before it has hardened sufficiently to bear it.

Sometimes, however, underpinning is done entirely in concrete. As long ago as 1834 a warehouse at Chatham,* the pile foundations of which had rotted and yielded, was underpinned in this way. Concrete, consisting of ground Halling lime (used hot), and Thames ballast, in the proportion of 1 to 6 (or 7), was used. It was deposited and well rammed in lengths of about 5 ft. at once, and 2 ft. wider than the walls, to a thickness of 3 ft. On the

* Burnell's "Limes, Cements, Mortars, &c.," in Weale's Series.

top of this bed a moveable framework was laid, consisting of two end pieces of iron crossing the wall and two planks one on each side of the wall, so arranged that the latter could be worked forward and backward by means of screws. When the planks were as far apart as was considered necessary, the rectangular space between them and the iron end pieces, was filled with concrete, and the planks were then forced closer together by means of the screws, effectually compressing the concrete against the superincumbent wall. The spaces left by the iron end-plates, which were about $\frac{3}{4}$ in. thick, were afterwards filled with grout. Some years afterwards, Lieut.-Col. Denison stated that no settlement had taken place since the work was completed. Now-a-days, such work would be carried out with Portland cement instead of lime, and the concrete would be so much the more reliable.

Caissons.—Iron caissons are frequently used for the foundations of bridges and other works in water, and are usually filled wholly or partially with concrete. These, however, do not fall within our province, but a word or two about concrete caissons or wells ought to be said, as these have been used on several occasions, not only for works in the sea, but also in marshy or light sandy ground.

They consist of a rim or cutting edge, frequently of wood and iron, on which is raised a concrete wall either in the form of a circle or a rectangle; the rectangular form is more easily built, but the circular form, although more difficult to construct on account of the shaped frames which are required, ought to be adopted, as such caissons can be sunk more regularly and are less liable to crack in sinking. In large caissons of rectangular shape, iron tie-bars are sometimes imbedded in the sides to prevent cracks. Hexagonal caissons would be less liable to crack than rectangular ones, and more easy to mould than circular ones.

The height of the first portion of the caisson may be about 5 ft. This is placed in position, and is sunk by men digging inside, or, when the water becomes too strong, by

excavating with chain-grabs or other contrivance. When the sinking has been continued far enough, another height of concrete is added to the caisson, and so on until a proper foundation has been reached. The sinking of the caisson is of course assisted by its own weight.

One of the first of these caissons was made by Mr. Bindon B. Stoney in Dublin Harbour, in 1863, to form the base of a beacon-tower. It was 19 ft. in diameter and weighed 80 tons. After it had properly set, it was conveyed down the River Liffey to its destination, a distance of about two miles, and was there placed in position, and lowered by excavating the ground within it, more concrete being added as the caisson sank.

At Colombo Harbour, Ceylon,* the depôt-wharf wall is founded on a double row of concrete cylinders, each section being 5 ft. in external diameter and 3 ft. 6 in. deep, the concrete being 12 in. thick. Another part of the wall is founded on cylinders 7 ft. in external diameter, the concrete being 15 in. thick; these cylinders were formed in sections 4 ft. 10 in. deep. The concrete in the lowest or cutting ring of each caisson was composed of 1 part Portland cement to 3 parts stone and sand; the concrete in the remaining sections was of 1 part cement, 2 parts sand, and 3 parts stone.

At Felixstowe tidal-basin † rectangular concrete caissons, 30 ft. by 20 ft. by 28 ft. deep, were used with walls 5 ft. thick, built on a curb of wood and iron, which was sloped down from the inside at an angle of 45 deg. to an outer cutting-edge of cast-iron. As the sinking proceeded, concrete was added in layers 3 ft. 3 in. high, until the caissons had reached a proper depth; 6 to 1 concrete was then filled into the caissons to a height of 7 ft., and 10 to 1 concrete for the remaining height.

SPRINGS.—Springs of water rising in the trenches are sometimes a source of difficulty. Col. Seddon in 1891

* *Proceedings of the Inst. C. E.*, paper by Mr. John Kyle, vol. lxxxvii. (1886-7), part i.

† Mr. John Russell, in discussion on Mr. Kyle's Paper.

mentioned the destruction of a concrete foundation by a spring of water, which was brackish and impregnated with red oxide of iron. The concrete would not harden. He overcame the difficulty by covering the soft concrete with a layer of asphalt to keep down the spring, and by depositing upon this a fresh stratum of concrete. He assumed that the soft concrete was as stable as an ordinary bed of gravel.

Another method is to cover a spring of water with canvas or tarpaulin, and in this way prevent it damaging the concrete.

GROUTING.—When a building has to be erected on a bed of good gravel, concrete may be unnecessary. Where, however, the gravel does not appear to be very firm, it can be effectually consolidated by means of thick neat cement grout. Experiments have shown that gravel or other aggregate, placed in a closed box, can be made into fairly good concrete by pouring cement grout through a tube into the box. The grout should be neat Portland cement, to which a little Roman cement may be added to hasten the setting. It should be used as thick as possible.

Thin grout does not set well, and grout containing sand is liable to give great inequality of strength, as the sand and cement easily separate, and one part of the grout may be nearly all sand, while another is nearly all cement.

MACHINE-BEDS.—Concrete is now largely used instead of masonry for the beds or foundations of engines, cranes, and other machinery. The bolts for securing the machines should have washers or plates at the bottom embedded in the lower part of the concrete. As stability is, in such foundations, of prime importance, a large factor of safety should be allowed.

CONCRETE IN WATER.—The method frequently adopted in small works is to construct a watertight dam by driving sheet-piles around the foundation into an underlying bed of clay, the adjacent edges of the piles being sometimes formed with a bird's mouth joint. In deeper and rougher water, the sheet-piling may be driven in two rows, the

space between being filled with clay. The water in the coffer-dam can then be pumped out, the excavation completed, and the concrete deposited.

Concrete is however frequently deposited *in* water, the trenches having been excavated by divers or dredgers. In the formation of sea-walls in this way, the shape of the wall is outlined by rows of piles, to which timber panels are attached. Concrete, actually deposited in water, should be 10 or 20 per cent. richer in cement, as some of this is inevitably washed away, and the concrete should be carefully lowered in self-opening boxes or skips.

Foundations of sea-walls are often formed of great bags of concrete, laid while the concrete is wet, so that the cement, oozing through the sacking, unites the different blocks together. Mr. Carey constructed the foundation of Newhaven Breakwater with two courses of 100-ton sack-blocks of concrete laid transversely and breaking joint; the blocks measured about 50 ft. by 7 ft. by 2½ ft. thick. The concrete at Newhaven usually consisted of 1 part Portland cement to 8 parts clean shingle and sharp sand. The faces of the breakwater, however, were of 1 to 6 concrete, and the hearting of 1 to 10.

Large hollow caissons of concrete are sometimes constructed on shore, then conveyed to their proper position and sunk, and are afterwards filled with concrete.

Huge solid blocks of concrete, weighing several hundred tons, are sometimes made on shore, and when they are sufficiently hardened, are towed or hauled into position and laid by means of divers.

Small concrete blocks, frequently dove-tailed, are also used to form the face of sea-walls, and behind them concrete is deposited in mass.

The proportions of the ingredients in concrete used for works in the sea vary according to the purpose for which it is required. In sheltered places and in the hearting of walls, 12 to 1 concrete is often used, while in exposed places and for face-work 4 to 1 or 6 to 1 must be employed.

THE "RANSOME" SYSTEM.—In this system twisted

wrought-iron bars are embedded in the lower part of the concrete to resist the tensile stresses in the projecting or cantilever portions of the foundation. The arrangement is shown in Fig. 20. A layer of concrete (1 cement to 3 aggregate) is first deposited to a thickness of 3 to 6 inches; the twisted bars are then laid transversely and pressed into the concrete at distances of 6 to 8 inches, and are covered

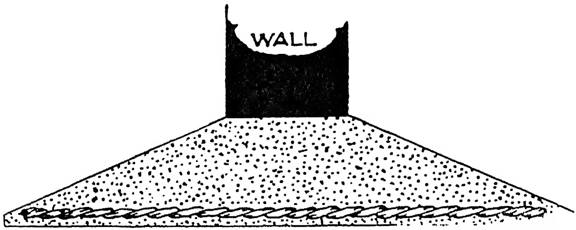


Fig. 20.—Concrete Foundation with Ransome's Twisted Iron Bars.

by another layer of 1 to 3 concrete 4 inches thick. The upper part of the foundation may be of 1 to 6 concrete. The different layers should be deposited as quickly as possible, so that they will set into a solid mass. Mr. Kidder, * has calculated the safe loads which may be placed on foundations of this kind from 6 to 20 feet wide, and some of his figures are given in the following table; the safe loads have, however, been converted into English tons.

TABLE XXIV., A.—CONCRETE FOUNDATIONS WITH RANSOME'S TWISTED IRON BARS.

Greatest Width of Concrete.	Greatest Thickness of Concrete.		Width of Wall or Footing above Concrete.		Distance between Centres of Bars.	Size of Square Bars.	Safe Load per Lineal Foot.	Size of Square Bars.	Safe Load per Lineal Foot.
Feet.	Ft.	Ins.	Ft.	Ins.	Inches.	Inches.	Tons.	Inches.	Tons.
18	3	3	5	6	8	2	68	$1\frac{3}{4}$	50
14	2	8	4	8	7	$1\frac{5}{8}$	62	$1\frac{3}{8}$	43
10	2	3	4	0	6	$1\frac{1}{4}$	58	1	37
6	1	8	3	6	6	$\frac{3}{4}$	48	$\frac{1}{2}$	26

* *Building Construction and Superintendence* by F. E. Kidder, Part I, page 43.

CHAPTER XIX.

PAVING, GROUND-LAYERS, AND FLOOR-SURFACES.

Artificial flags—Curbs, &c.—Flags on piers—Paving-blocks—*In sitû* paving—Concrete-rollers—Stable floor—Cracks—Ground-layers —Floor-surfaces—1. *Concrete*, 2. *Tiles*, &c., 3. *Wood-blocks*, &c., 4. *Boards*, 5. *Kamptulicon*, &c.—Relative resistance to wear of different floor-surfaces (Table XXV.).

THE use of concrete for paving is extending rapidly both in buildings and in streets. Miles upon miles of footpaths in London and elsewhere have been formed with concrete, either deposited *in sitû* or laid in the shape of flags. And although we could point to many failures of concrete deposited *in sitû*, to great cracks and honeycombed surfaces, yet, on the other hand, we could point to paving which, after years of heavy traffic, seems as perfect as it did a month after it was laid.

One objection, which is frequently raised against a concrete footpath deposited *in sitû*, is the difficulty of cutting through it whenever it is necessary to connect the drains, or water-pipes, or gas-pipes of buildings adjoining the footpaths with the mains in the streets, and the further difficulty of making the paving good after it has been so cut. This objection has had so much weight that most town-surveyors or engineers prefer to use the concrete in the form of flags, and the manufacture of such flags has within recent years been considerably extended.

ARTIFICIAL FLAGS.—The patent Victoria Stone is a well-known kind of concrete largely used in the shape of flags. It consists of one part of Portland cement and three parts of "granite" chippings not much larger than peas, cast in

metal-lined moulds, and when set, steeped in a solution of silicate of soda. Part of the silica of the solution is given up and combines with the free lime of the cement, and apparently hastens the induration of the concrete. The flags are afterwards washed with clean water and allowed to harden before use. The compressive strength of this stone is said to surpass that of the best sandstones; while in imperviousness, it is said to be better than Bath and Portland stone, about equal to the best sandstones, but considerably inferior to granite, syenite, and good trap and basalt. The "granite" used in the manufacture is really a syenite from the Groby quarries in Leicestershire, which, according to Rivington's *Notes*, weighs 173·4 lb. per cubic foot.

The Imperial Stone, formerly known as Silicated Stone, is another well-known concrete. It consists of 1 part Portland cement mixed with 3 parts crushed granite, the largest dimension of any piece of which does not exceed three-eighths of an inch. The dust formed in crushing the granite is carefully washed away, as otherwise it would prove, as we have shown, a source of weakness. The cement and aggregate are mixed by machinery, and filled into metal-lined moulds, the upper surface (which is really the under surface of the flag when laid) being smoothed with a trowel. In order to condense the soft concrete as much as possible, the mould containing it, is placed upon a "trembler," that is, a bench to which a pair of quickly-revolving cams impart a rapid vibratory motion. By this means, the flags are rendered more dense and durable.

When the concrete has set sufficiently, the flags are removed from the moulds, and packed for some days in tanks filled with a solution of silicate of soda.

Another well-known kind of paving is that made by the Croft Granite Brick and Concrete Co., and known as "Croft Adamant." This is made like the ones already mentioned, of Portland cement and crushed syenite, the latter being quarried in part of the company's property. These ingredients are mixed by machinery, and rammed into wooden frames. The upper surface is finished and thoroughly

well trowelled, by hand. These flags, therefore, differ from the Victoria and Imperial Stone flags, in that the wearing surface is carefully formed by hand, instead of being simply left as cast in the mould. It is argued that by this method of manufacture a denser surface is obtained, and the danger of pin-holes on the surface, due to excess of water in the concrete, is avoided. Sometimes the flags are finished for a certain thickness (say, half or three-quarters of an inch), with coloured concrete, usually red; the effect is pleasing.

Granite-concrete flags of good quality are also made by W. B. Wilkinson & Co., Stuart's Granolithic Paving Co., and many other makers, the ingredients in nearly every case being Portland cement and some kind of granite or syenite. Whinstone and slag are, however, sometimes used.

The durability of the best artificial flags is beyond question. They do not crack or scale away, but have a hard dense structure. On the other hand, there is much artificial flagging which, on account of bad materials or workmanship, or insufficient cement, soon presents a honeycombed surface, and wears rapidly away; while some is porous in consequence of the ingredients having been mixed too dry.

Some artificial paving can be obtained with impressed patterns, which have a good appearance and improve the foothold; while other paving is supplied in various shapes, sizes, and colours, and can then be laid in simple patterns.

The usual thickness of artificial flagging is from 2 in. to $2\frac{1}{2}$ in., the usual breadth is 2 ft., and the length varies by 6 in. from 1 ft. 6 in. to 3 ft. 6 in.

CURBS, &c.—Granite-concrete curbs and channels are largely used for the sides of footpaths, where artificial flagging is adopted.

FLAGS ON PIERS.—Mr. Lascelles advocates the formation of an air-space under artificial flagging in dwellings by means of small concrete piers, on which the corners of the flags are supported; this air-space prevents the rising of damp through the floor.

PAVING-BLOCKS.—In addition to artificial flags, which of

course are only suitable for foot-traffic, concrete paving-blocks of several kinds are now made for vehicular traffic. Such are the patent paving-blocks of Croft Adamant; each block is about 18 in. wide, 30 in. long, and 3 in. thick, and has two longitudinal V-shaped grooves, and two half-grooves along the edges, as shown in Fig. 21. The concrete used in these blocks is of a coarser kind, in order that the surfaces may not wear slippery; the pieces of syenite vary in size up to 2-in. cubes. The blocks are

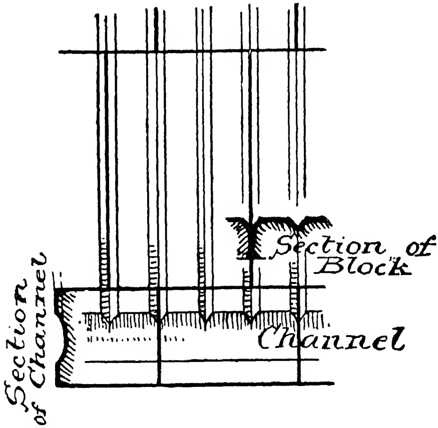


Fig. 21.—Croft Paving-Blocks and Channel.

laid with the grooves running across the road, so as to give good foothold to horses, and concrete channels are made for the sides of the road with grooves across one edge of the channel to correspond with the grooves of the paving.

Maclean's patent paving-blocks are of cement-concrete with "rings, strips, or small blocks of lead" inserted flush with the surface to prevent wear.

Other paving-blocks are made with cubes of syenite or other hard material inserted by hand into the concrete while it is soft, and left projecting about half-an-inch above the general surface of the block.

In situ Paving.—But while artificial flags are useful for the footways of streets, there are many situations in which a jointless slab of concrete is much better, such as the floors of basements, or of rooms on the solid ground, or of stables, cow-houses, &c. In these cases a floor is required which, while having a durable surface, also prevents the rising of moisture and of subsoil air, and the percolation of foul water and sewage into the ground beneath. Some kind of concrete flooring, deposited *in sitû*, and without joints, should then be adopted.

The Patent Victoria Stone Co. prefers a foundation of broken brick about 4 in. thick, upon which is laid in one operation a layer of concrete 2 in. thick, composed of 1 part Portland cement and 3 parts finely-crushed and machine-washed granite.

Another kind of *in sitû* paving is laid by the Imperial Stone Co., and is known as "Petro-silicon." Where heavy traffic is expected on the paving soon after it is laid, the surface is treated with silicate of soda in order that the hardening may be hastened.

Stuart's Granolithic Paving has a layer of cement-and-gravel concrete 2 or 3 in. thick, and a finishing coat of cement and crushed granite 1 or 1½ in. thick, the whole being laid on a foundation of broken brick or stone.

Concrete footpaths have been largely used in this country and in the United States. Gilmore recommends them to be laid on beds of well-compacted sand or gravel to allow for sub-drainage. The rough concrete should be 3½ or 4 in. thick, composed of 1 part Rosendale or other cement, 2½ parts sand, and 5 broken stone and gravel, well rammed, and with the surface afterwards roughened by scratching. Upon this, the finishing coat of Portland cement mixed with 2 or 2½ parts of "clean fine sand" [*sic*] is laid, and rammed to a finished thickness of about ½ in., the surface being neatly smoothed with a trowel. The pavement should be covered, as soon as it is finished, with hay, sand, &c., to protect it from the sun, for ten days or more, and then with a layer of damp sand "to prevent wear for two or three weeks."

A more recent American specification requires a foundation (5 in. thick) of coarse gravel, broken stone, sand or ashes, well rammed or rolled, on which a layer of concrete (1 cement, 1 sand, and 3 gravel) is spread to a thickness of 3 or 4 inches and well rammed; before this has begun to set, the finishing coat, composed of cement and sand or cement and clean crushed granite in equal proportions, must be applied with a trowel to a thickness of 1 in., and carefully smoothed and levelled between straight-edges or "screeds."

The following method of laying *in sitû* paving is recommended by Messrs. W. B. Wilkinson & Co. When the ground, after being excavated to the proper depth, is soft, it must be well rammed, or, in bad cases, a layer of common concrete must be laid, the upper surface being left 6 in. or 7 in. below the intended finished floor-line. On good consolidated ground, a layer of brick-bats or stone-rubble is spread and then broken, so as to form a layer about 4 in. thick; the breaking helps to consolidate the ground still more. (When a common concrete foundation has been laid, the brick-bats or rubble should be broken before being spread.) There should be no soil or small stuff among the broken material, and this should be laid roughly to the various gradients required. On the broken material, the proper concrete pavement is laid down soft and finished with a smooth or grooved surface as required. For moderately light traffic, as in coach-houses, warehouses, footpaths, gentlemen's stables, &c., the paving is usually laid about 2 in. thick, and a thickness of 3 in. is found enough for the heaviest horses, carts, rolling casks, &c.

For stables, stable-yards, conservatories, sloping-ground, and other places where liquid-manure or water would otherwise spread over the whole surface, or where a good foothold is necessary, the surface of the concrete should be indented or grooved, and channels formed for drainage where required.

CONCRETE-ROLLERS.—The indents for giving a rougher surface to concrete paving may be conveniently made by means of Gilchrist's small brass rollers with projecting

teeth, such as that shown in Fig. 22. These rollers are made from $5\frac{1}{2}$ to 9 in. long, and $3\frac{1}{2}$ or 4 in. in diameter.

Grooves for affording surface-drainage and foothold at the same time, may be made by small brass rollers having one or more projecting V-shaped ribs, similar to the one shown in Fig. 23. The ribs are of various sizes, but make grooves varying from $\frac{1}{4}$ to $\frac{1}{2}$ in. deep, and from $\frac{3}{8}$ to $\frac{3}{4}$ in. wide at the top. Larger sizes can, of course, be obtained. Rollers are also made of different designs from the foregoing, such

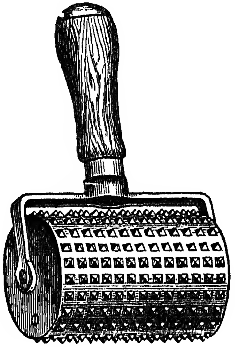


Fig. 22.—Brass Roller for Indenting Concrete Paving.

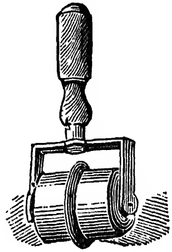


Fig. 23.—Brass Roller for Grooving Concrete Paving

as "crimpers," which form a series of V-shaped ridges and hollows, but the ones mentioned are most frequently used.

Stable Floor.—Fig. 24 is a plan of a stable floor, showing the diagonal V-shaped grooves in the stall at A A, passing into the larger V-shaped or semi-circular channel at B, which in turn leads into the main channel at C. The last may be formed to receive an iron grate as shown in Fig. 25, or may consist of a stoneware or iron gutter bedded in the concrete. A raised footway is provided at D D, which may be grooved to almost any pattern, although it must be remembered that the simplest patterns can be most easily swept clean. Straight grooves across the foot-

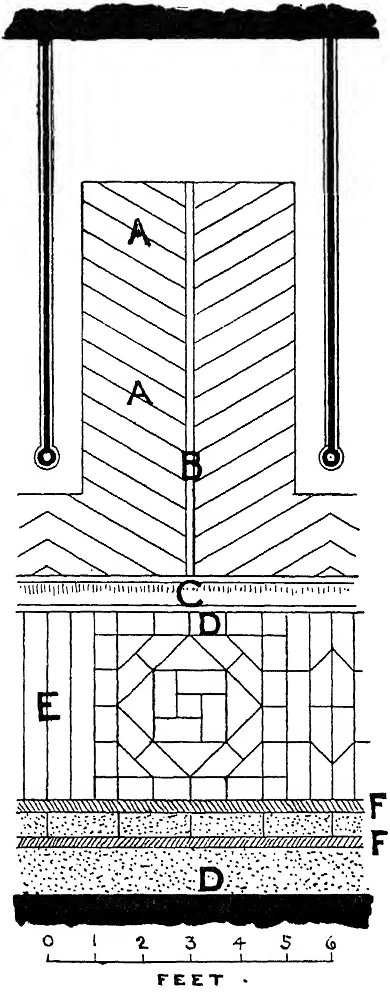


Fig. 24.—Plan of Stable Floor.

way, as shown at E, are the best in this respect. Plain margins are left around each stall and wall, so as to be more easily swept. The use of diagonal "crimpers" is shown in the border at F F.

A good effect is obtained by adding red or other colouring matter to the concrete of the gangway for the whole or part of its width, as shown by the dotted portion in the figure.

Where brick paving is adopted for stables, &c., it is best to deposit for the reception of the bricks a 6-in. layer of concrete, laid to the proper gradients. The surface of the concrete can be finished with a $\frac{1}{2}$-in. coat of cement mortar (1 to 1, or 1 to 2), in which the bricks can be bedded; the joints of the bricks should be carefully made with the same mortar, and then grouted over with neat cement grout.

Cracks.—The expansion and contraction due to changes of temperature frequently cause cracks in large areas of paving exposed to the weather. These cracks are not only unsightly, but also allow water to find its way into the concrete, and render the latter liable to destruction by frost. The difficulty can be overcome by forming the paving into separate slabs by means of wood laths about $\frac{3}{8}$ in. thick, placed in the concrete every 8 ft. or 10 ft. These lathed joints allow for expansion and contraction.

Ground-Layers.—A common method of forming base-

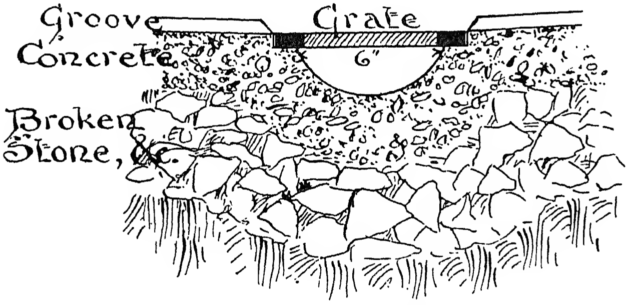


Fig. 25.—Section of Channel and Grate in Stable.

ment-floors, especially in towns where a 6-in. layer of concrete over the whole site of a building is required by the by-laws, is to deposit concrete 5 in. or 6 in. thick, as shown in Figs. 14 and 15, pp. 219 and 221, and finish the surface of this in one of the various ways hereafter mentioned.

As this concrete is intended to keep down moisture and subsoil air, it should be as impervious as possible, and for this reason a considerable proportion of sand and small gravel should be used in its composition, so that all interstices may be well filled; *e.g.*, the concrete might consist of 1 part Portland cement or good hydraulic lime, 2 parts clean sand, 1 part pea-gravel, and 3 parts gravel, stone, or brick, broken to pass a $1\frac{1}{4}$-in. ring. Coke-breeze and similar aggregates of coarse open texture should not be used in

ground-layers, as, besides absorbing moisture, they afford accommodation for vermin, which may eventually, through some unsuspected crevice, find access to the rooms above.

FLOOR-SURFACES. 1. *Concrete.*—The pavings already described may be used for the floors of houses and other buildings, but the total thickness of the concrete in floors laid on the ground is generally specified in the by-laws of public authorities to be not less than 6 in.

The surface of concrete floors can be economically finished with a thin coat, $\frac{1}{2}$ in. or $\frac{3}{4}$ in. thick, composed of Portland cement and clean coarse sand or sharp grit, well trowelled. This ought to be applied before the rough concrete has set, in order that the whole may set into one mass. Granite sand gives better results than ordinary sand. Pea-gravel, from which all sand has been screened, is sometimes used with good results, and wears less rapidly than a mortar containing sand in the same proportions.

For rough work, neat cement is sometimes worked into the concrete foundation with a hand-float and trowel, but without leaving any coating on the surface.

It may here be remarked that all floor-surfaces containing cement are improved by being frequently washed or wetted during the first few months of their existence. Unless this is done, the dry, warm air of houses, &c., abstracts all the moisture from the concrete, and prevents the due hardening of the cement. It is largely owing to this cause that many cement floors are friable and yield a large amount of dust.

Clean crushed crystalline limestone, quartz, and granite, from which all dust has been removed, form better aggregates than sand for surface-coats. They should be passed through $\frac{1}{4}$-in. or $\frac{3}{8}$-in. screens, and mixed with neat Portland cement in the proportion of 1 part cement to 2 parts aggregate, and should be laid so as to finish 1 in. or $1\frac{1}{2}$ in. thick, well beaten, and trowelled to a smooth surface.

Ornamental concrete floors can be produced by using aggregates of different colours embedded in Portland cement, which can also be coloured if desired. White spar, marble, greyish-green slag, pink or grey granite, dark-grey

syenite, and other materials can be employed with good effect. Cubes of granite, &c., screened through two sieves (the one to eliminate the fine particles, the other the large pieces), and with the irregular-shaped pieces picked out by hand, can be obtained for the purpose. The cement with which they are mixed can be coloured a rich red by means of ground red hematite, or Venetian red, and other colours can be obtained by means of various mineral colouring-matters—blue by German ultramarine, browns by various oxides of iron, black by black manganese. Nearly all colouring-matters, however, reduce the strength of cement, and in some cases the loss of strength is so great as to render the concrete extremely friable and porous.

The ingredients should be thoroughly mixed, spread upon the rough concrete bed, well rammed, and finished level or with the necessary falls, the surface being thoroughly well smoothed with a trowel. The finished thickness of this surface-layer should not be less than $\frac{3}{4}$ in., and is seldom more than $1\frac{1}{4}$ in.

Terrazzo is the name now generally applied to a finishing coat of polished concrete. To receive this, the rough concrete must be rendered with cement mortar (usually 1 cement to 2 sand), finished to a true and level surface. The terrazzo is, as a rule, $\frac{3}{4}$ in. in thickness, and is composed of cement and marble dust, in the surface of which small pieces of marble are embedded. In the cheapest kind, the cubes are irregularly distributed, but for better work larger pieces of marble (up to $\frac{3}{4}$ or 1 inch on the face) are "sown" by hand on the surface. The marble may be entirely of one kind (usually white), or variety may be obtained by a mixture of different colours, white, yellow, red, green, black, &c., or by forming the central portion of one colour or a mixture of colours, and the borders of other colours (usually darker than the central portion). The polishing is begun immediately after the floor is laid, and is effected by means of smooth stones attached to wooden handles, water being applied somewhat freely during the operation. Coloured cement is sometimes used, but it is much better to rely for the colour-effect entirely on the marble.

At the Hotel Métropole, Brighton, nearly six acres of floors are formed with Stuart's Granolithic Paving, upon which cloth-felt is spread to receive the carpets. And at the Savoy Hotel, London, nearly all the floors, which consist of steel joists and coke-breeze concrete, are simply finished on top "with neat cement."

2. *Tiles, &c.*—The best foundation for floor-tiles and mosaic is a layer of concrete about 6 inches thick, floated with a $\frac{1}{2}$ or $\frac{3}{4}$ in. coat of cement mortar (about 1 to 2) to a perfectly level surface. The top of this coat should be left $\frac{1}{4}$ in. *plus* the thickness of the tiles, below the proposed floor-level. The $\frac{1}{4}$ in. is allowed for the coat of quicksetting cement, in which the tiles are bedded.

The tiles used for floor-surfaces are usually encaustic tiles, glazed or unglazed, and are made from different clays coloured as required and properly burnt. Tiles, however, are now made of Portland cement and granite-sand, coloured throughout their thickness. The tiles are usually plain, although ornamental ones with patterns in two or more colours, can be obtained. The colours, that can be used with Portland cement without damaging it, are few in number and do not yield as brilliant an effect as encaustic tiles. A rich red colour is the most satisfactory, and a good deep blue is also available; buff, brown, black, and a rather disagreeable green almost complete the range. If the cement used in these tiles is not thoroughly air-slaked, fine hair-cracks appear on the surface. Small pin-holes, due to excess of water in the mixing, are also somewhat frequent, but are of little detriment to the wearing power of the tiles.

Marble-mosaic tiles are a kind of concrete, consisting of cement and random tesseræ of marble, compressed and polished like terrazzo. They have a pleasing effect, can be had of various colours, and are durable.

3. *Wood-blocks, &c.*—In the case of wood-blocks and parquetry, when the surface-coat on the concrete layer is hard, a layer of bituminous composition must be spread upon

it to receive the blocks. There are, however, several systems of wood-block flooring in which metal keys are inserted in the concrete for the purpose of giving additional security to the blocks, or in which small cubes of wood are inserted to which the blocks can be secured with screws or metal discs.

4. *Boards.*—Building-owners frequently exhibit a partiality for ordinary boarded floors, even when fire-resisting construction is adopted. Sometimes ordinary boards are laid upon the concrete layers in basements without any intervening joists or bituminous composition. Such floors should have a first layer of good dry broken stone or brick, then a layer of impervious concrete 3 in. or 4 in. thick, and

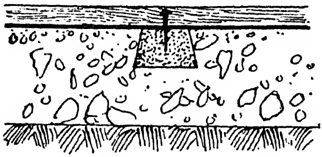


Fig. 26.—Concrete Floor with Boards nailed to continuous lines of Wright's Fixing-Blocks.

finally a 2-in. layer of coke-breeze concrete (1 to 4), brought to a perfectly level surface. When this has dried sufficiently (which will not be in less than three or four weeks), the floor-boards can be laid and nailed directly to the coke-breeze concrete. Mr. C. F. Moxon, in *The Builder* for Sept. 8, 1888, declares that there is no danger of dry-rot; we think, however, that a thin coat of bituminous composition, spread over the concrete as for wood-blocks, would be an additional safeguard.

For upper floors, of course, there is no reason why the boards should not be nailed directly to the concrete, if coke-breeze concrete be used. This is frequently done, and it has the advantage of eliminating all spaces where dirt and vermin could accumulate.

When the floors are not composed of coke-breeze con-

crete, some other method must be adopted. An excellent system consists in the use of Wright's patent fire-proof fixing-blocks (which are as cheap as wood fillets of similar section) as shewn in fig. 26. These have a sectional area of $4\frac{1}{2}$ in. by $2\frac{3}{4}$ in. and are made in 12 in. lengths. They are laid end to end in continuous lines from 18 to 24 in. apart, and narrow flooring-boards, about $1\frac{1}{2}$ in. thick, are nailed directly to them, without any space being left under the boards. These are cheaper than blocks. A thin layer of bituminous composition should be spread on the concrete, if this is on the solid ground. Sometimes a packing of slag wool is laid between the concrete and the boards.

Sometimes strips of coke-breeze concrete are laid upon the other concrete, and to these the boards are nailed, as shewn

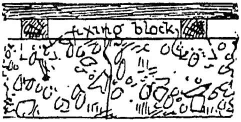


Fig. 27.—Boarded Concrete Floor with Wood Fillets secured to Fixing-Blocks.

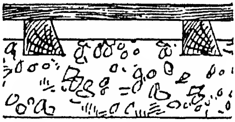


Fig. 28.—Boarded Concrete Floor with Dove-Tailed Wood Fillets.

in Fig. 33, p. 276; or small dove-tailed wood-blocks are inserted in the concrete, to which small wood fillets (2 in. by $1\frac{1}{2}$ in., or thereabouts) are nailed, and to these the boards are secured, as in Fig. 27. Substitutes for the wood-blocks can be found in Wright's concrete fixing-blocks, or in Jabez Thompson's brickwood fixing-blocks. Sometimes the fillets themselves are cut to a dove-tailed section, and imbedded in the concrete, as in Fig. 28, but the insertion of wood into concrete in this manner is not to be recommended.

Objection is frequently taken to the cavities left in the floors by the various systems of boarding on wood fillets. Certainly they harbour dirt and vermin, and are, therefore, sanitarily imperfect, but they have the advantage of deadening the sound to some extent, and in solid concrete floors the transmission of sound is a great disadvantage. When

necessary, the cavities can be filled with coarse concrete, slag-wool, coke-breeze, &c.

5. *Kamptulicon, &c.*—Still another method of finishing concrete-floors is sometimes adopted, and that is to glue kamptulicon, "cork-carpet," or similar material to the level floated coat on the concrete. The "cork-carpet" is especially to be recommended, as it deadens the sound of footsteps to a considerable degree.

RELATIVE RESISTANCE TO WEAR OF VARIOUS FLOOR-SURFACES.—The resistance to wear of several kinds of stone was considered in Chapter XI. The best materials were found to be quartzite, quartz, porphyry, basalt, and trap-rocks; good granite and syenite were about 20 per cent. inferior. The best syenite or granite, of the four kinds from Great Britain which were tested, was found to be the pink Leicestershire syenite, and the worst was the *black* Guernsey syenite, Aberdeen granite being about midway between the two.

According to the *Thonind. Zeitung*,* some recent tests of various floor-materials yielded the "co-efficients of wear" given in the next table. A column showing the relative value of the different materials is now added.

TABLE XXV.—RELATIVE RESISTANCE TO WEAR OF VARIOUS FLOOR-MATERIALS.

No.	Material.	Co-efficient of Wear.	Relative Value.
1	Porphyry	6·7	100
2	Basalt	7·1	94·3
3	Granite	8·3	80·7
4	White Marble	24·4	27·5
5	White Sandstone†	72·7	9·2
6	Parquetry slabs from G. Behne	15·3	43·8
7	Plaster composition by "Rabitz" patent	49·2	13·6
8	*Portland cement and normal sand,* 1 to 1	15·3	43·8
9	" " 1 " 2	17·1	39·2
10	" " 1 " 3	32·4	20·7
11	" " 1 " 4	53·1	12·6
12	" " 1 " 5	124·2	5·5

* See *The Builder* for April 16, 1892.

† This was undoubtedly a very weak sandstone; many sandstones give better results than ordinary granites. See p. 128.

This table goes to show that good Portland-cement mortar (1 to 2) forms a better floor-surface than *some kinds* of marble and sandstone, and is about equal to the best parquetry. We do not know the age of the cement-mortars, but certainly it would not be less than 28 days, and it ought in fairness to have been considerably more, as the adhesive strength of cement increases largely with age. Another important point, which is emphasised by these results, is that mortars containing 2 parts of sand to 1 of cement are only slightly inferior to those containing sand and cement in equal quantities, but beyond the proportion of 2 to 1, sand detracts from the resistance more and more rapidly. Thus, if we take the value of 1 to 1 mortar as 100, 1 to 2 will be 89·5, but 1 to 3 will have only about one half the value of the latter, namely 47·2, while 1 to 4 will have less than one-third (28·8), and 1 to 5 less than one-seventh (12·3).

These results are in accord with practice, for it has been empirically ascertained that for floor-surfaces consisting of Portland cement and sand, 1 to 2 mortars are the weakest that can be satisfactorily adopted. When cubes, however, are used instead of sand, the joints in a given bulk of aggregate are considerably smaller in area, and consequently a smaller quantity of cement may be added. The bulk of the cement is sometimes therefore only one-third or even one-fourth that of the cubes. Safer proportions, however, are 1 to $1\frac{1}{2}$ for good coarse sand, and 1 to 2 for good cubes.

CHAPTER XX.

FLAT CONCRETE FLOORS WITHOUT IRON.

"Be bold; be not too bold"—Cheapness—Formulas VIII. to XII.—Example—Beam-constants give too low results with fixed slabs—Safe-load constants deduced from actual floors—Strength yet incalculable—Actual examples of floors, &c. (Table XXVI.)—Col. Seddon's tests of supported slabs (Table XXVII.)—Deductions—Fixing the edges—Composition—Scaffolding—Removing the scaffolding—Ceilings—Girders.

"Be bold; be not too bold."—Much has been written and said at different times about the advantages and disadvantages of flat concrete floors without iron, but there can be no doubt that architects have been somewhat chary of adopting them. Here and there an architect, bolder than the rest, has constructed such floors, even of large spans. One by Mr. Frank Caws measures no less than 26 ft. 6 in. by 19 ft. 6 in. with a thickness of only 7 in. (except for a width of 9 in. around the edges, where the concrete is thickened out into a cove). But examples like this are few and far between, and the more we study the subject, the more shall we wonder at the boldness displayed in such construction.

Concrete, as we have already explained in the beginning of the sixteenth and seventeenth chapters, is not a suitable material for resisting transverse stress, on account of its exceedingly small tensile strength, and the reasons there advanced against the use of concrete beams, apply with equal cogency to the subject now under consideration.

Cheapness.—The cheapness of concrete floors without iron is the argument usually adduced in their favour, and

when the cost of such floors is compared with that of the ordinary concrete floors, in which steel or iron joists of uniform section and strong enough in themselves to carry the whole load, are imbedded, there is undoubtedly a considerable balance in favour of the former. But this is not a fair comparison, for a concrete floor containing joists as just described, is an unscientific piece of work, more unscientific even than a floor of concrete only. A concrete beam or slab lacks tensile strength while it has as a rule quite enough compressive strength. What is needed then, is an addition only to its tenacity, in order to render its tensile and compressive resistances equal to one another. The addition of iron and steel in the upper half of a concrete floor is, in ordinary cases, sheer waste of material. On the other hand, iron and steel in the lower half of the floor increase its strength largely with the least amount of these materials, and the cost of such a floor will compare favourably with a solid concrete floor of similar strength.

As, however, such slab floors are sometimes used and can safely be used for small spans, such as corridors, it is necessary to consider their strength.

FORMULAS.—The strength of a *square* plate, fixed at the edges and uniformly loaded, may be calculated from the following formula based on one of Grashof's, where w = breaking-weight in cwt. per *square foot*, L = length of each side in *feet*, and t = thickness in *inches* :—

$$w = 4\,C\,\frac{t^2}{L^2} \quad \ldots \quad \ldots \text{(VIII.)}.$$

This formula is extremely simple, and may be put into a still simpler form, which can be more easily remembered. Let W = the total distributed load; that is to say, $w \times L^2$. We then get :—

$$w \times L^2 = 4\,C.\frac{t^2}{L^2} \times L^2,$$

which gives us the simple formula :—

$$W = 4\,Ct^2.$$

In other words, all square plates or slabs of whatever size but of the same thickness, fixed at the edges and uniformly loaded, will carry the same total load.

The weight of the slab itself is, of course, part of the load, and consequently, as the size of the slab is increased, the less does the difference between its weight and the breaking weight become, until ultimately we reach that size of slab the weight of which is more than the actual breaking load. In such a case, the slab will collapse, by its own weight, as soon as the centres are removed.

The formula for *supported* square plates, uniformly loaded, may be taken to differ from formula VIII. in the same ratio as formula XII. differs from XI., and will therefore be as follows :—

$$w = \frac{16}{5} \, C \, \frac{t^2}{L^2}, \text{ or } W = \frac{16}{5} \, Ct^2 \quad \ldots \quad \ldots \text{ (IX.).}$$

The strength of *rectangular* plates, fixed at the edges and uniformly loaded, may be calculated from the following formula, where B = breadth of slab in *feet* :—

$$w = 2C \frac{L^4 + B^4}{L^4} \times \frac{t^2}{B^2} \quad \ldots \quad \ldots \text{ (X.).}$$

Circular plates, of radius R. (in *feet*), *fixed* at the edges and uniformly loaded, may be calculated thus :

$$w = \frac{3}{2} \, C \, \frac{t^2}{R^2} \quad \ldots \quad \ldots \text{ (XI.).}$$

Circular plates, *supported* at the edges and uniformly loaded, require the formula

$$w = \frac{6}{5} \, C \, \frac{t^2}{R^2} \quad \ldots \quad \ldots \text{ (XII.).}$$

That is to say, the ratio between uniformly-loaded circular plates *fixed*, and similar plates *supported*, appears to be as 100 is to 80 ; the ratio between uniformly-loaded beams, *fixed* and *supported*, has been already stated to be as 100 is

to 66. If these be correct, the ratio for rectangular plates may be expected to hover between them, being practically the same for square plates as for circular ones, and approximating more and more to the ratio for beams as the slabs become more and more elongated.

In the four formulas just given, the length and breadth of the slab are stated in *feet*, and the thickness in *inches*, for convenience of calculation. The weight is stated per square *foot*, and this adjusts the equation, so that the value of C should be the same both for beams and slabs. For purposes of comparison with the formulas given in Chap. XVI. for beams, it would have been better to have had the terms the same. Such comparison can, however, be instituted even now without great difficulty. It will be found that uniformly-loaded *square* slabs, *fixed* on all *four* edges, are theoretically twice as strong as similar slabs fixed on only *two* opposite edges, and three times as strong as similar slabs only *supported* on two opposite edges.

EXAMPLE.—Find the uniformly-distributed breaking weight at the age of twenty-one days, of a concrete floor having a clear span of 14 ft. 6 in. by 13 ft. 6 in., and a thickness of 6 in., supported around the edge; the concrete to be composed of 1 part Portland cement and 4 parts broken brick.

The co-efficient of rupture of such concrete is shown by No. 6 in Table XXII. (p. 190) to be 3·11 at the age of forty-three days. The strength at twenty-one days will be about four-fifths of that at forty-three days, *i.e.*, about 2·5.

The slab is so nearly square that it may be calculated as a slab 14 ft. square, and we may proceed by the help of formula IX. :—

$$w = \frac{16}{5} \times 2{\cdot}5 \times \frac{6^2}{14^2},$$

from which we calculate that $w = 1{\cdot}46$ cwt. Therefore W (the total breaking weight) $= 1{\cdot}46 \times 14{\cdot}5 \times 13{\cdot}5 = 285{\cdot}8$ cwt.

If the weight of the slab itself, which will be about

105 cwt. (calculated at 120 lbs. per cub. ft.), be deducted from this, we find that the added load required to break the floor will be about 180 cwt. or 9 tons.

A floor of the dimensions, age, and composition given in this example, *supported* at the edges, was actually made and broken by Col. Seddon. It gave way under a distributed load of $10\frac{1}{2}$ tons. This is rather more than the breaking weight obtained by calculation. But we must remember that great care was taken by Col. Seddon in the construction of the floor; the concrete was well rammed, and was covered with water for seven days after being deposited, in order that the cement might not fail to harden through loss of moisture by absorption, evaporation, &c. We are not told that these precautions were taken by Col. Crozier with the beam from which our constant was calculated.

BEAM-CONSTANTS GIVE TOO LOW RESULTS WITH FIXED SLABS.—The values of C found for different kinds of concrete beams (such as those given in Table XXII., pp. 190—1), are usually employed in the five formulas, VIII. to XII. Professor Unwin, in his *Elements of Machine Design*, declares that "some experiments by Mr. R. Wilson (*Engineering*, vol. xxiv., p. 239) appear to shew that the ultimate resistance of flat plates is considerably greater than that obtained by putting C = the breaking stress in the above formulæ. These formulæ are strictly applicable within the elastic limit only, and Mr. Wilson's plates may have been dangerously strained long before giving way. They did take a large set."

The safety of large concrete floors, which are actually in use, also points to the conclusion that the formulas for slabs, fixed all round, declare the strength of such slabs to be too little. There is little doubt that a concrete slab fixed all round really becomes, when loaded, a kind of flat dome, exerting a horizontal thrust against its supports or abutments, just in the same way that a concrete beam becomes an arch.*

* See Mr. C. Colson's tests, pp. 195—7.

SAFE-LOAD CONSTANTS DEDUCED FROM ACTUAL FLOORS.—As an instance in point, we may adduce the floor mentioned by Mr. C. Drake at a meeting of the *Royal Institute of British Architects* in 1876.* This floor was "nearly" 20 ft. by 15 ft., only 6 in. thick, was (presumably) fixed all round, and carried a distributed load of 2 cwt. per sup. ft. without deflection. Assuming the floor to be 20 × 15, it gives, according to formula X., a *safe-load* constant of 4·74 if the weight of the concrete itself be taken as part of the load, and of no less than 5·92 if the load of 2 cwt. per sup. ft. be, as is probably the case, in addition to the weight of the concrete.

Mr. Drake did not state the composition of the concrete, but, allowing a moderate factor of safety, the constant would really be greater than either of the constants for neat cement given in Table XI., p. 72. Comparison with the *breaking-load* constants in Table XXII. shews that these, with one exception, are inferior to the *safe-load* constant deduced from Mr. Drake's floor. It is, of course, possible that Mr. Drake was speaking quite generally as to the load on the floor, and that it might not reach 2 cwt. per sq. ft., but this cannot account for the whole of the discrepancy, for the mere dead weight of the floor itself (calculated at only 112 lbs. per cub. ft.) would, according to the formula, give a *safe-load* constant of 1·18.

Some concrete floors in a warehouse designed by Mr. Frank Caws, measure 21 ft. by 12 ft. 6 in., by about 13 in. thick, and six years after they were built, Mr. Caws found "considerable areas loaded with four and five cwt. per sq. ft." A load of 5 cwt. (including the weight of the concrete), gives a safe-load constant of 2·05, if calculated according to formula X.

Another floor, constructed under the direction of Mr. Caws, measures 26 ft. 6 in. by 19 ft. 6 in., and only 7 in. thick. For a width of 9 in. around the edges, the concrete is formed in the shape of a cove or continuous

* See *R. I. B. A. Transactions*, 1876.

corbel; if we make full allowance for this, the net size of the slab will be 25 ft. by 18 ft. The actual weight of the floor itself, assuming the concrete to weigh 120 lbs. per cub. ft., is $\frac{5}{8}$ cwt. per sq. ft., which gives a *safe-load constant* of no less than 1·63 for the dead weight alone If we say that, in addition to this, the floor was loaded with only 70 lbs. per sq. ft., we get a safe-load constant of 3·26, which is rather more than the *breaking-load* constant deduced from a *supported* beam of similar composition, namely 1 part Portland cement, and 4 parts broken brick.

The dead weight alone of an ancient concrete floor in the Atrium Vestæ at Rome gives a *safe-load* constant of ·7, which is undoubtedly large considering the kind of cementitious materials to which the Romans were confined. The floor measures 20 ft. by 20 ft. by 14 in., and the concrete has been assumed to weigh 132 lbs. per cub. ft.

Sufficient has been said to shew that, while the formulas just given for fixed slab floors may not be wrong in ratio (*i.e.*, for fixed slabs of different sizes), they at any rate give too low a strength if the constants obtained from supported beams be used with them. Higher constants may with safety be adopted.

The reason for this is not far to seek. The formulas were originally devised for calculating the strength of wrought-iron plates, which are practically as strong to resist tension as compression. It is probable that they would give approximately accurate results with all materials thus balanced; for example, the constants, deduced from the breaking of concrete beams containing sufficient iron in the lower half to render the tensile and compressive resistances of the beams practically equal, could probably be used in the formulas for fixed slabs with a near approximation to correctness. But it is evident that the formulas cannot be used with beam-constants for fixed slabs composed of a material like concrete, which has a compressive resistance about ten times its tenacity.

STRENGTH YET INCALCULABLE.—Unfortunately no experiments have been made with concrete slabs, *fixed* on all

sides, and therefore there are no data available from which a table of constants for fixed slabs can be deduced. Under these circumstances, it is necessary to consider actual floors, and from them to deduce approximate safe-load constants in the way already indicated, or to use existing floors as a basis from which the safe dimensions of suggested structures can be empirically ascertained. The latter is the rough-and-ready method, the former is the safer, but by neither method nor by any formula yet published can the strength of a concrete floor be accurately predicated. There are too many unknown or doubtful quantities, such as the indurating quality of the cement, the nature of the aggregate, the completeness of mixture, and, last but not least, the nature of the strains set up in the slab.

Actual Examples of Floors, &c.—A few actual examples, collected from accredited sources, will therefore prove useful. The following table contains examples, not only of flat slab-floors, but also of floors and roofs with arched soffits, and of balconies, the whole being given together for convenience of comparison and reference. The balcony No. 16, at the age of eighteen months, was loaded with 177 lbs. per sq. ft., and bore it safely; this test gives a *safe-load* constant of 1·5, calculated according to formula VII., as a beam 11 in. thick, and this, considering the age, is what might have been expected from a comparison with No. 6, Table XXII.

Practice appears to prove that theory gives wrong results when applied to fixed slabs, and therefore theory must not be relied upon. But experiments by Col. Seddon induce the belief that the formulas and beam-constants may be used in making calculations for floors which are merely *supported* at the edges.

Col. Seddon's Tests of Supported Slabs.—These experiments, which are the only ones worthy of the name which have been carried out on concrete slabs, were made by Col. Seddon in 1874, and are given in Appendix I. of his "Builder's Work and the Building Trades" (1886

TABLE XXVI.—EXAMPLES OF CONCRETE FLOORS, &C., WITHOUT IRON.

No.	Length.	Breadth.	Thickness.	Where used.	Authority.	Remarks.
Flat Slabs.	ft.	ft.	in.			
1	20	20	14	Atrium Vestae, Rome.	Prof. Middleton.	Ancient Roman Work.
2	6	6	3	Footway of bridge	F. Caws.	...
3	14·5	7	6	Brigade-Depôts...	Col. Seddon	1 P.c. to 4 breeze, slag, brick, or burnt clay, to pass $\frac{3}{4}$-in. mesh.
4	10	10	4	...	F. Caws.	...
5	12·5	11·5	6	...	C. A. Adams.	...
6	21	12·5	13	Warehouse........	F. Caws	1 P.c. to 4 brick.
7	26·5	19·5	7	...	„	Thicker for 9 in. around margin, 1 P.c. to 4 brick.
Arched Slabs						
8	...	9	12 to 5	Stables	W. B. Wilkinson.	Granite-concrete.
9	...	9·5	11 „ 4	Corridor	„	„
10	50	12	11 „ 3	Warehouse........	Broughton	Carrying "immense weight of machinery and men."
11	...	12	15 „ 6	Pantechnicon......	Lockwood.	...
12	19	13	11 „ $4\frac{1}{2}$	House	J. Tall.	...
13	40	16	„ „ „	Drawing Room ...	„	...
14	70	16·5	7 „ $3\frac{1}{2}$	Roof of Barn	Trench	Intrados rising 1 in. per ft. of span,—1 P.c. to 5 gravel.
15	90	20	15	„ „ Warehouse	W. C. Street	Segmental arch with 3 ft. rise.—1 P.c. to 5 Thames ballast.
Cantilevers.						
16	...	4	8 to 3	Balcony	Potter	1 P.c. to 5 brick.
17	50	4	11 „ 3	„	Broughton	1 P.c. to 4 ballast (part, 1 to 6).

edition). Other experiments have been made, but some of them have been of no benefit to the public, as the published results are lacking in some important particular, either the thickness or composition of the concrete is omitted, or the position of the load is not defined, or it is not stated whether the slabs were fixed or only supported.

The following table gives the results obtained by Col. Seddon on slabs, *supported* all round, and uniformly loaded with layers of bricks. In calculating the value of C, it is assumed (see Formula X., *et seq.*, p. 255) that the strength of slab No. 4, which is nearly square, is 20 per cent. less than if the edges had been fixed, and that of the remaining slabs 25 per cent. less.

TABLE XXVII.—COL. SEDDON'S TESTS OF CONCRETE SLABS, SUPPORTED AT EDGES.

Number.	Composition.			Length between supports.	Breadth between supports.	Thickness.	Age in days.	Breaking weight, per sq. ft.	Weight of slab, per sq. ft.	Total breaking weight, per sq. ft.	Calculated value of C.
	Portland Cement.	Sand.	1-in. crushed brick.								
				ft.	ft.	in.		cwt.	cwt.	cwt.	
1	1	0	4	14·5	6·75	6	7	3	·54	3·54	2·85
2	1	0	4	,,	,,	,,	14	2·76	,,	3·30	2·66
3	1	0	4	,,	,,	,,	21	8·88*	,,	9·42	7·58*
4	1	0	4	,,	13·5	,,	,,	1·07	,,	1·61	2·90
5	1	·75	3	,,	6·75	,,	14	2·51	,,	3·05	2·45
6	1	·75	3	,,	,,	,,	21	2·84	,,	3·38	2·72

The brick was broken to pass a one-inch mesh. The concrete was well rammed and covered with water for seven days. In the last two examples, only three volumes of brick were used, but three-fourths of a volume of sand were added. The concrete was therefore slightly richer than in the first four cases, but the result was not satis-

* This cracked under a load of 6½ cwt. per sq. ft., but did not break under the load of 8·88 cwt. per sq. ft., which was the greatest load available for putting upon the slab. Evidently the slab was near its breaking-point; its strength is strangely abnormal. Perhaps the bricks, which must have been piled to the height of 7 ft. or 8 ft., were aid to break joint, and formed a flat arch or dome, which, to some extent, relieved the pressure upon the central portion of the slab.

factory, and Col. Seddon concludes that the addition of sand is injurious to the strength of concrete.

If we take into consideration the relative ages, we find that the constants deduced from the foregoing experiments are, with the exception of No. 3, remarkably near the one calculated from a beam of the same composition (No. 6, Table XXII., p. 190).

Mr. Frank Caws has advocated the use of flat concrete floors with a little cove all around at their bearing on the walls, as shewn in Fig. 29; this gives a slightly domical form to the floor, and increases the strength, although to what extent is not known.

Deductions.—The practical lessons to be learned from these investigations are that concrete may be used in the form of slabs for floors of moderate span, but that such floors are liable to give way *suddenly* when overloaded, or when overheated and suddenly cooled; further, that the strength of such floors cannot be foretold with any degree of accuracy on account of the great diversity of the material, and the lack of sufficient data for calculations. They are, however, economical, and there is no reason why they should not be used in houses and other buildings where they will not be subjected to intense heat or heavy impingent loads, up to spans of 10, 12, or even (with care) 14 feet. Large floors can be divided into bays of 7 or 8 ft. by means of steel or iron girders, on which the concrete slabs may rest. Lastly, great care must be taken that all the edges of the floors are securely fixed, in order that the strength of the slabs may reach the highest possible limit, although this highest limit cannot be accurately ascertained.

Fixing the Edges.—Wherever practicable, solid concrete floors should be laid when the walls are at the height to receive them, and the walls should then be built upon the concrete.

In many cases, however, it will need considerable insistence on the part of an architect before he can induce a contractor to adopt this course, and frequently it will

happen that some other method must be tried. The best method perhaps is to form a continuous corbel and chase in the brickwork as shewn in Fig. 29. The brick corbel-courses could be moulded if required, or could be covered with a plaster cornice, or in some other way. This method has the advantage of lessening, in a slight degree, the span of the floor.

Where a corbel-course is not desirable, a chase can be formed in the wall, if its thickness will permit. A depth of 4½ in. from the face will be found sufficient, and the chase can be filled during the erection of the wall by bricks

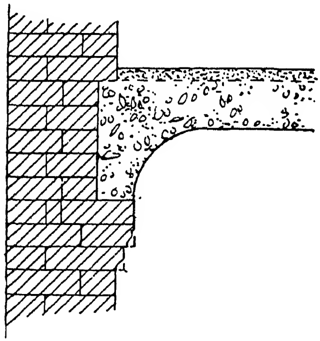


Fig. 29.—Corbel-Course and Chase for Edge of Concrete Floor.

laid in dry sand, having headers however laid in mortar every 5 or 6 ft. The bricks in the chase can be knocked out little by little, as the concrete floor is being deposited. This method has been adopted by Mr. Caws, but he does not like it, although he has not known any mischief to arise from it; great care is required.

Still another way would be to insert in the wall a channel iron of suitable size. As this would be entirely surrounded with fire-resisting materials, there would not be much danger of damage being done to it by an ordinary conflagration. Especial care should be taken to ram the concrete into the chases, so as to fill them completely.

Composition.—Sufficient has perhaps been said in previous chapters to enable the reader to decide on the composition of concrete for floors. Lightness and strength are the points to be chiefly considered. Fire-resistance is also important. Lightness depends mainly on the aggregate, and therefore coke-breeze is frequently used. Coke-breeze, furnace-clinker, and broken brick or pottery, are the aggregates most frequently adopted for floors. They should, as a rule, be broken to pass an inch mesh. Gravel and broken stone are unsuitable. The less sand that is used the better. Portland cement is the strongest matrix, but plaster of Paris and allied cements, which are lighter and at the same time weaker, may be used.

The proportion of cement to aggregate should not be less than one volume to four or five. It is better to use a rich concrete and a thinner floor, than a poorer concrete and thicker floor. A rich concrete is likely to be of more uniform strength than a poor one, as there is great difficulty in mixing the latter so thoroughly as to have every particle of aggregate coated with cement, the result being that dry joints occur here and there.

Scaffolding.—Concrete floors are usually deposited on wooden scaffolding. Where large girders cross the floor at intervals, longitudinal bearers with wedges under are laid along the lower flanges, and joists are laid between them at the proper level and covered with close-jointed boards. Sometimes the bearers are supported in putlog holes in the walls, or are carried by uprights resting on the floor below. In any case, great care must be taken that the scaffolding is stiff enough to carry the wet concrete without the slightest appreciable deflection. The scaffolding should be higher at the centre of the span rather than lower, in order that the arched or domical strength of the floor may not be lost by the sagging of the woodwork. It is a great advantage for the scaffolding to be supported on wedges, like the centring of an arch, so that the strain can be thrown gradually upon the floor, when the scaffolding is "struck."

Removing the Scaffolding.—The question of the age

at which scaffolding may be struck is often raised. One writer gravely remarks that, as a concrete slab 12 in. wide, 6 in. thick, and 13 ft. span will carry 8·3 cwt. at the end of a week, and as the weight of the slab will be only 7·8 cwt. between the supports, "it follows that the supporting staging may be struck with safety at the end of a week." Probably he would never repeat the statement if he stood under such a slab on the eighth day, while the centres were being removed. A mere difference of half-a-cwt. between strength and dead-load is not enough for a slab containing 13 sq. ft.; it allows a margin of only $8\frac{1}{2}$ lbs. per sq. ft. Verily, "even that which they build, if a fox go up, he shall even break down."

The irreducible minimum for slab floors of Portland cement concrete ought to be fixed at 21 days, but this is really too little, and the longest time which can possibly be allowed, ought always to be given. Some architects specify that the centres shall not be struck in less than a month, others insist on five weeks, but in all cases even longer time may elapse with advantage. This is an important point, as several floors have been strained and have collapsed on account of the scaffolding being removed too soon.

With plaster of Paris and allied cements, the centres are often removed in three or four days, but a week ought really to be allowed, and longer whenever practicable.

Ceilings.—The ceilings of concrete floors are sometimes formed by a thin skimming coat of ordinary "fine stuff" or "gauged stuff" only, but this is liable to fall off if the floor is subjected to moving loads, as the concrete affords little key for it. It is best to employ a skimming coat of the same material as the matrix in the concrete, whether it be Portland cement, or plaster of Paris, or any other cement. Sometimes dovetail blocks or fillets are inserted as described for floors, and wood or wire or "expanded metal" lathing is secured to them, on which the plastering can be executed; this makes good work, not liable to crack or fall, but the blocks are a source of weakness. Fibrous

plaster slabs are well adapted for fixing under concrete floors, especially when coke-breeze is the aggregate employed, as in this case the slabs can be nailed directly to the concrete.

An excellent method of forming concrete floors which shall have the lower surface perfectly smooth, is that introduced by Mr. Frank Caws. When the wood staging under the proposed floor is in position, it must be covered with a "thin skin of plaster of Paris floated up perfectly level and fair. Upon this . . . . a grout of pure cement and water is thinly spread, and upon this grout the concrete proper is cast, and beaten down in the usual manner. The skin of plaster of Paris is perfectly watertight. Not a drop passes through it, and thus the concrete sets more slowly, and to better purpose; and when the centring is eventually removed, the plaster comes away with it, and leaves the concrete solid ceiling smooth and fair, without a blemish or defect."*

Floors of considerable length are sometimes constructed with iron or steel girders about 10 ft. apart, over which a concrete slab is formed somewhat after the manner illustrated in Fig. 33. The girders should be protected from fire as shewn in that figure or in fig. 44. When, however, girders occur, it will usually be best to take advantage of the extra depth of the floor and to throw the concrete into an arched form, which gives greater strength for the same quantity of material.

* *The Builder*, July 27, 1889.

CHAPTER XXI.

FLAT COMPOUND FLOORS OF CONCRETE AND IRON, &c.

Variety of floors—Development—Systems: 1. "Fox and Barrett" and modification of same, 2. Phillips's or Measures's, 3. Dawnay's, 4. Allen's, 5. Hyatt's "Gridiron-Tie" floor and Simmons's adaptations of the same (inequality of strength, transversely and longitudinally), 6. Floors with ⊥-iron ties, 7. Ward's steel-webbed floor, 8. "Monier," 9. Lindsay's trussed rod floor (advantages of network of iron), 10. Homan and Rodgers's, 11. Moreland's, 12. Brownlie and Murray's girder and floor, 13. Lindsay's steel trough floor, 14. Moreland's ditto, 15. Lindsay's concrete-slab floor, 16. Fawcett's fire-proof flooring (Table XXVIII.), 17 & 18, Homan and Rodgers's "Flat-brick" and tubular-lintel floors, 19. Willis and Astley's, 20. Corrugated iron centring—Girders—Columns.

Variety of Floors.—The number of the different kinds of fire-resisting floors in which concrete is employed, is legion, and it will certainly not be advisable for us in a work of this kind to enter closely into the details of the wood, iron, steel, terra-cotta, fire-clay, and other materials, which are in various ways combined with concrete to form fire-resisting floors. Something, however, must be said to show the principal systems, which have been, or still are, in use.

Development.—From the days when pugging between wood joists was the only fire-resisting floor in general use, vast strides have been made. The first step was taken at the beginning of the century, and consisted in the adoption of brick arches between cast-iron girders. These were superseded by rolled girders and brick arches. Sir William Fairbairn followed with rolled iron girders about 10 ft. apart, between which plate iron, $\frac{1}{4}$ in. thick, was riveted

in an arched form; upon this arch, which was apparently intended to carry all the load on the floor, concrete was laid and finished with flags, cement, &c. The cost of the iron caused the floor to be very expensive.

The next step in this direction was the substitution, by Moreland, of corrugated iron for plain plates. The iron was, however, still regarded as fire-proof, and therefore as needing no protection. The underside of the corrugated iron arch and the bottom flanges of the girders were exposed, and it was not until attempts were made to protect the iron, that the modern systems of fire-resisting floors could be said to have begun.

1. "*Fox and Barrett*" *Floor.*—But contemporaneously with these developments of the arched floor, was the progress of the flat system. The first flat fire-resisting floor of concrete and iron appears to be that originally introduced about 1830 but afterwards improved, and known as the "Fox and Barrett" floor. It consisted of rolled iron joists, about 20 in. apart, with main girders in addition for large spans. Between the joists, wood fillets about $1\frac{1}{4}$ in. square, and $1\frac{1}{2}$ in. apart were laid, and upon these the concrete was deposited. The ceiling was plastered in the usual way, the plaster extending under the iron joists. This marked an important step—the protection of the iron, —although it must be confessed that the protection was very limited.

First use of Fire-clay Lintels.—A modification of this system was adopted at the Liverpool Exchange about 40 years ago. Instead of the wood fillets, hollow triangular tiles, or, as they would be called to-day, "fire-clay lintels," were used. This seems to be the germ from which several of the most successful modern systems have sprung. The difference between the germ and the offspring is that in the former the lintels rested on the bottom flanges of the iron, leaving the underside of the iron unprotected, while in the latter the ends of the lintels are grooved and the flanges of the joists fit into the grooves and are consequently protected underneath by the projecting lips of the lintels.

2. *Phillips's or Measures's Floor.*—In 1862, a further modification of the "Fox and Barrett" system, known as "Phillips's Patent Fireproof Floor," was introduced by Measures Bros., and met with great success. The rolled iron joists were spaced further apart (about 3 or 4 ft.), and ⊥-iron supports about 9″ apart were laid between them, in place of the wood fillets in the preceding system. More recently light rolled iron joists have been used instead of the ⊥-irons, but without much reason, we think. Measures's system still left the lower flanges of the joists unprotected, but in more recent years this defect has been modified by keeping the temporary wood staging under the floor about an inch below the joists, so that the concrete will pass under them.

3. *Dawnay's Floor.*—Apparently this device of protecting the iron joists by the concrete was originated by Archibald Dawnay, whose floors have been extensively used during the last 35 years or more. Like the foregoing flat floors, rolled iron joists about 5 in. deep are used, but at distances up to about 7 ft. For small bays ½ in. square iron bars 12 in. apart are laid from joist to joist, and for larger bays iron joists 3 in. deep and 18 in. apart are used. The iron is protected underneath by at least 1½ in. of concrete. The latter consists of Portland cement and brick (preferably fire-brick). It is said that a floor weighing 40 lbs. per sq. ft. will carry a safe load of 2 cwt. per sq. ft. over a span of 12 ft.

4. *Allen's Floor.*—In 1862 Allen patented his combination of iron and concrete for use in floors, lintels, &c. This system, which by the way is very similar to a French system introduced about the same time, is extremely interesting, as it only just misses being theoretically more perfect than most others, which have been devised either before or since that date. Wrought iron bars about 3 in. by 1 in. are placed on edge about 2 ft. apart, the ends being built into the walls; across the bars ½ in. iron rods are laid, likewise 2 ft. apart, and secured to the bars with wire. Concrete is then deposited around the bars, but, it is said,

to the depth of only 4 in. Such a thickness is not enough to protect the iron properly, and, as in most other systems, the compressive strength of the concrete is not taken full advantage of, for the iron in the upper half of the floor is practically the same as that in the lower. The same network of iron used with concrete 6 or 7 in. thick (exclusive of any concrete protecting the iron underneath) would be theoretically, strength for strength, more economical, as the iron could give tenacity to the structure without adding needlessly to its compressive resistance. In the adaptation of his system to lintels, Allen has borne this point in mind, and has kept the iron to the lower half only.

Allen's concrete consisted of Portland cement mixed with four or more volumes of crushed slag, clinker, or coke.

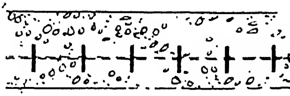


Fig. 30.—Hyatt's "Gridiron Tie" Floor.

5. *Hyatt's "Gridiron-Tie" Floor.*—The development of concrete floors containing iron in the lower half only, is undoubtedly largely due to the experiments of Mr. Thaddeus Hyatt, some of which we have already quoted. These were carried out in 1877, and have proved of great value. Several combinations of iron and concrete have been designed by Mr. Hyatt, but the one illustrated in Fig. 30 is among the simplest and most economical. It consists of iron bars placed on edge a few inches apart, having round iron rods threaded through them at the same distances. The size and distance of the bars and rods vary according to the span. So far Mr. Hyatt's system differs little from Allen's. The chief differences, however, are in the relative positions of the iron and concrete. Mr. Hyatt insists on the iron being protected underneath by about 2 in. of concrete, and makes the upper part of the floor entirely of concrete, thus trusting it to bear its share of the burden.

The results of the tests of compound beams given in Table XXIII., p. 210, proved conclusively that the use of iron ties in concrete beams was not a mere theoretical fancy, but was of practical value. And it has been proved that floors can be safely and economically constructed on the same principle.

Mr. William Simmons in *The Builder* for Dec. 6, 1888, describes floors, which he has constructed, similar to Mr. Hyatt's "Gridiron-Tie Construction" which we have just illustrated. For a floor 19 ft. by 15 ft. he used 4 in. by $\frac{1}{4}$ in. wrought iron bars placed on edge 2 ft. apart, with $\frac{1}{2}$ in. round rods passing through holes in the bars also 2 ft. apart; between each pair of bars a $\frac{1}{4}$ in. square rod was laid on the round rods. Coke-breeze concrete 7 in. thick was well rammed around and above the iron grid, and was finished with an inch surface coat of granite-grit and cement.

Another floor, however, more fully exemplifies the iron-tie construction. This was a floor over a stable 20 ft. by 60 ft. The iron bars were $\frac{1}{2}$ in. thick and only $2\frac{1}{2}$ in. deep, but they were placed no more than 9 in. apart. Half-inch rods were used at the ends only of the bars, where they rested in the walls. The total depth of the concrete in this floor was no less than 12 in.

Mr. Simmons says that the floors were put in as the walls arrived at the levels to receive them. This insures the proper fixing of the edges of the concrete.

Inequality of Strength, Transversely and Longitudinally.—One disadvantage appertaining to most floors of this type is that the iron is much stronger in one direction than the other. Thus, in Mr. Simmons's first floor, the 4 in. $\times \frac{1}{4}$ in. bars have a sectional area (deducting $\frac{1}{2}$ in. for the holes) of $\frac{7}{8}$ sq. in. in each 2 lin. ft. of floor-breadth, while the $\frac{1}{2}$ in. rods have an area of only $\frac{1}{5}$ sq. in. in each 2 lin. ft. of floor-length. This does not matter as long as the floor is supported or fixed on two opposite sides only, and the stronger bars run from support to support. But when the floors are attached on all four sides, the result is that

the floor is weaker in one direction than the other, and the advantage, which ought to accrue from fixing all the edges instead of two only, is reduced almost to zero.

In order to equalise the strength in both directions, five-eighth inch round rods 8 in. apart might be used with the 4 in. × $\frac{1}{4}$ in. bars 2 ft. apart.

The end bars should lie entirely within the thickness of the wall, and the ends of the rods should be threaded through them and bent so as not to be drawn out by the strain to which they may be subjected.

Interlacing Rods.—The expense of boring or punching holes through the bars, and the consequent weakening of the bars, may be avoided by passing alternate rods alternately over and under them instead of through them; thus,

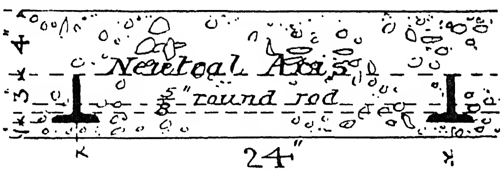


Fig. 31.—Floor with ⊥-iron ties.

the first rod might pass over the second bar and under the third, and so on, while the second rod would pass under the second bar and over the third. The rods are sometimes arranged in pairs.

The latter method is adopted in some of W. H. Lindsay, Neal, & Co.'s floors, as shown in Figs. 34 and 45.

6. *Floors with ⊥-iron Ties.*—Instead of simple upright bars, light rolled joists could be used to give the required tenacity, and these would afford a better key to the concrete; but it would be still better to employ ⊥-irons, as in these the great bulk of the metal is concentrated at the greatest distance below the neutral axis. Such an arrangement is shown in section by Fig. 31.

The ⊥-irons are 3 in. wide, 3 in. deep, and $\frac{1}{2}$ in. thick, placed 24 in. from centre to centre, and crossed by $\frac{5}{8}$ in

round rods 6 in. apart. Pairs of interlacing rods might be used 12 in. apart.

The same reasoning which was applied to beams of concrete and iron (Chapter XVII.), may be applied to the floor under consideration, although the calculations will be somewhat more intricate.

Fig. 32 is an enlarged section of the ⊥-iron, the limiting stress on which may be placed at 5 tons per sq. in., *i.e.* 11,200 lbs. Assuming the neutral axis to pass through the middle of the floor-thickness, the metal web just reaches to it, and the stress on the metal will at that point be *zero*. As already explained, the stress varies gradually between

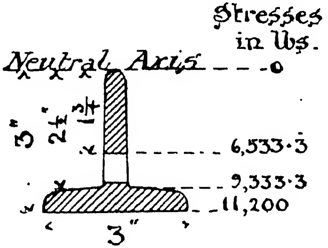


Fig. 32.—Enlarged section of ⊥-iron, shown in Fig. 31.

these extremes, so that at the upper side of the flange it will be 9333·3 lbs., and at the upper side of the hole for the tie-rods it will be 6533·3 lbs.

If we assume the safe working resistance of the concrete to be 400 lbs. in compression and 40 lbs. in tension we can proceed with our calculations.

The Compressive Resistance of the upper half of the beam will be

$$(24 \text{ in.} \times 4 \text{ in.}) \times \frac{400 \text{ lbs.}}{2} \times (\tfrac{2}{3} \text{ of } 4 \text{ in.}) = \begin{array}{c}\text{Inch-lbs.}\\ 51,200\end{array}$$

The Tensile Resistance of the lower half of the beam will be the sum of the resistances of the concrete and the iron.

1. *Concrete*,

Inch-lbs.

$$(24 \text{ in.} \times 4 \text{ in.}) \times \frac{40 \text{ lbs.}}{2} \times (\tfrac{2}{3} \text{ of } 4 \text{ in.}) = \quad 5{,}120$$

2. *Wrought Iron*,

a. Flange,

$$(3 \text{ in.} \times \tfrac{1}{2} \text{ in.}) \times \left(\frac{9{,}333{\cdot}\dot{3} + 11{,}200 \text{ lbs.}}{2}\right) \times 2{\cdot}8 \text{ in.} = 43{,}120$$

b. Web,

$$(1\tfrac{3}{4} \text{ in.} \times \tfrac{1}{2} \text{ in.}) \times \frac{6{,}533{\cdot}\dot{3}}{2} \times (\tfrac{2}{3} \text{ of } 1\tfrac{3}{4} \text{ in.}) = \quad 3{,}334$$

Total . . 51,574

In other words, the resistances of the upper and lower halves of the floor are theoretically equal, and the addition of iron to the upper half is unnecessary. Too much reliance must not be placed upon theoretical deductions alone, but since practice has shown that floors can be constructed with metal in the tension half only, we may conclude that theory has not led us very far astray. In the present calculations a factor of safety of five has been used, and this is the least that ought to be adopted.

Col. Seddon has constructed concrete floors with the tie-metal in the form of large man-of-war's cables, crossing and re-crossing each other, and thoroughly embedded in the concrete.

7. *Ward's Steel-Webbed Floor.*—A very interesting recent development of concrete floors containing metal-ties is the "Patent Steel-Webbed Fireproof Solid Concrete Floor," made by Messrs. B. Ward & Co. This is shown in Fig. 33, and consists of one or more layers of steel-webbing or network embedded in concrete. There is no possibility of the webbing being pulled through the concrete, as sometimes happens in the case of rods. It is said that floors of this kind, only 5 in. thick, can be made to carry 3 cwt per sq. ft. over a span of 7 ft.

8. "*Monier.*"—The "Monier" system, which has achieved great success on the Continent, consists of iron wires embedded in strong concrete, and marvellous examples of its use are recorded. Flat floors, 13 ft. square and only

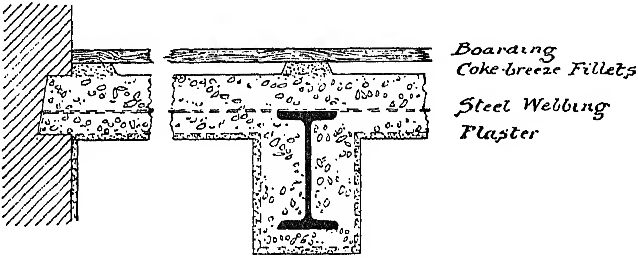


Fig. 33.—B. Ward & Co.'s Steel-Webbed Floor.

2 in. thick, have been constructed without any iron beams; many of the floors constructed by Stuart's Granolithic Stone Co. are of similar character.

9. *Lindsay's Trussed Rod Floor.*—W. H. Lindsay, Neal,

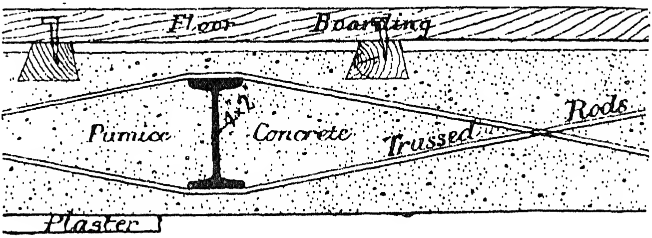


Fig. 34.—Lindsay, Neal, & Co.'s Trussed Rod Floor.

& Co., construct floors of steel or iron joists interlaced with trussed rods and embedded in "pumice-concrete," as shown in Fig. 34. They can be made, it is said, to carry from 1 to 20 cwt. per square foot. The joists, of course, vary in size according to the span, and are usually laid 24 in.

apart. The interlacing rods are placed in pairs about 18 in. apart. For a span of 10 ft., 4 in. by 2 in. joists, 24 in. apart would enable the floor to bear safely a load of $1\frac{1}{2}$ cwt. per square foot. The so-called pumice-concrete consists of Portland cement, sand, and coke-breeze, and is said to weigh only about 80 lbs. per cubic foot. Nails can be driven into it and will be held by it, so that wood fillets are not needed, although they are shown in some of the illustrations published by the company.

ADVANTAGES OF NETWORK OF IRON.—One great advantage of all floors containing a network of iron joists or bars and rods, is that the concrete is entangled among them, and cannot therefore fail totally under a heavy load, or under the influence of fire. This is an important consideration, as concrete alone is liable to collapse suddenly and disastrously.

10. *Homan & Rodgers's.*—A flat floor of concrete and iron was patented by Homan & Rodgers in 1865, and another in 1871. The subject-matter of the later patent seems to have been the joists, which were called the "Patent Economic (rolled) Joist;" they were apparently of the ordinary I-section. The concrete was deposited from about an inch below the joists to a depth of 2 or 3 in. above them.

11. *Moreland's.*—Moreland's floor, brought out in 1866, had for its special distinction light lattice or bowstring girders, 3 ft. 9 in. apart, instead of solid webbed joists. The concrete was therefore continuous throughout, and not divided into distinct masses by the ironwork.

12. *Brownlie & Murray's.*—A recent invention, which attains the same end, is the "Arch and Invert" girder, patented in 1885 and manufactured by Brownlie & Murray. These girders are shown in Figs. 35, 36, and 37. Fig. 35 is an elevation of the girder, and Figs. 36 and 37 are longitudinal and transverse sections respectively of concrete floors containing **I** or **⊥**-iron joists passing through and carried by the girders, the whole of the iron being embedded in concrete. The distinctive feature of the girders is in the

web, which consists of U-shaped angle-irons riveted to the webs of the ⊥-irons which form the top and bottom flanges. By this means a series of oval openings is formed in the web of the girder, through which joists and concrete can pass. The girders are made of various depths, from 7 in. to 18 in. and upwards if required. There is no doubt that they will prove of service for fireproof floors, as by their use the depth of the floors is reduced, and the concrete is rendered continuous.

So far we have treated of flat floors, which have required

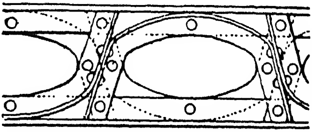


Fig. 35.—Elevation of "Arch and Invert" Girder.

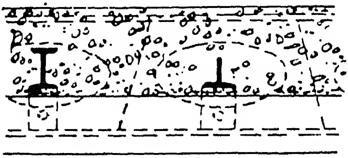


Fig. 36.—Longitudinal Section of Floor showing Joists passing through Girder.

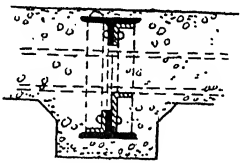


Fig. 37.—Transverse Sections through Girder and Floor.

temporary scaffolding to receive the concrete, and in previous chapters we have shown that such scaffolding should remain in position for several weeks. This often entails considerable inconvenience, and it becomes questionable whether a floor, which can be constructed without scaffolding, should not be adopted.

13. *Lindsay's Steel-Trough Floor.*—Reference may first be made to W. H. Lindsay, Neal, & Co.'s patent steel bridge-decking, which is also adapted for the floors of ware-

houses and other buildings where great strength is required. It will be seen from Fig. 38 that the decking consists of steel troughs riveted together and filled with concrete. Some protection is necessary for the underside of the floor, and this is afforded by the blocks of pumice-concrete, shown in the figure, or by a plastered ceiling carried on fillets bolted to the underside of the troughs.

Lindsay's decking is made in depths from 4 in. to 12 in., the former being sufficient to carry a safe load of 2 cwt. per square foot over a span of about 15 ft., and the latter over a span of about 40 ft. The weight of the 4-inch decking (exclusive of concrete) is 15½ lbs. per square foot, and that of the 12-inch nearly 35 lbs.

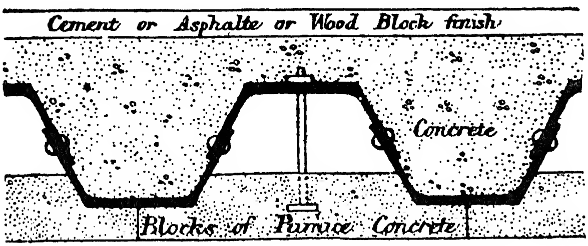


Fig. 38.—Lindsay, Neal, & Co.'s Steel-Trough Floor.

14. *Moreland's Steel-Trough Floor.*—Moreland's steel flooring is somewhat similar to the last, but the troughs are of rectangular section, and are built up of plates and single or double angles.

Steel-trough floors are, however, expensive, on account of the large quantity of metal which they contain. Temporary scaffolding can be dispensed with in other ways. The method most germane to our subject may be first mentioned, *viz.*, by using concrete or cement slabs carried between the joists. The slabs may be either in the form of lintels or of arch-blocks. Examples of such floors are more common on the Continent and in America than in England.

15. *Lindsay's Concrete-Slab Floor.*—Several floors of this kind are, however, in use in this country, such as Lindsay's concrete-slab floor, shown in Fig. 39. Rolled joists are fixed 2 ft. apart, and on their lower flanges cast slabs of pumice-concrete, about 24 in. by 18 in. by 4 in., are carried, the metal being entirely protected by them. The slabs are grouted with cement, and may be covered with ordinary concrete, so that the joists are completely surrounded. The ceilings are plastered directly to the slabs.

The more common material used to carry the concrete in such floors, is fire-clay, as this offers greater resistance to fire than concrete does. Several systems, combining fire-

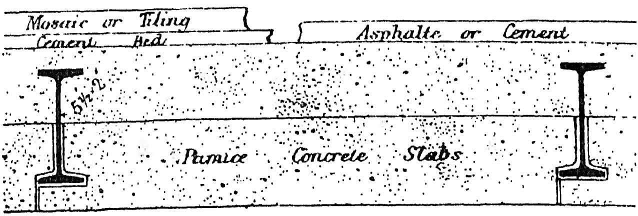


Fig. 39.—Lindsay, Neal, & Co.'s Concrete-Slab Floor.

clay lintels, iron or steel, and concrete, are now in use, the best known, perhaps, being "Fawcett's Fireproof Flooring," shown in Figs. 40 and 41.

16. "*Fawcett's Fireproof Flooring.*"—"In the construction of this fireproof floor the special feature is a *tubular lintel* or hollow tube made in fire or red chimney-pot clay, and burned mellow.

"Iron joists (of sections to suit the spans and loads) are placed at 2 ft. centres, and the lintels are fixed between with their diagonals at right angles to the joists. The end of each bay is squared by cutting (during manufacture) an ordinary lintel parallel to the diagonal; the piece cut off, when reversed, goes on the other end. Thus the ends and sides of all lintels are open next the walls.

"The lintels being in position, specially prepared cement-concrete is filled in between and over them, which takes a direct bearing upon the *bottom* flange of the joists, thus relieving the lintels of the floor-load, which is taken by the iron and concrete, the lintels forming a permanent fire-proof centering, reducing the dead weight of the floor 25 per cent., and saving about half the concrete.

"Cold air is admitted (through air-bricks in the external walls) into any of the open ends or sides of the

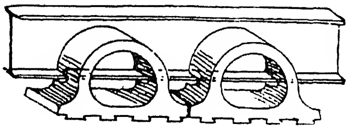


Fig. 40.—View of Joists and Lintels before the Concrete is deposited.

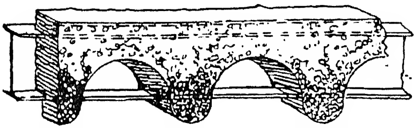


Fig. 41.—View of Joist and Concrete with Lintels removed.

FAWCETT'S FIREPROOF FLOORING.

lintels, and passes through them from bay to bay under the joists.

"The flat bottom of the lintel completely encases the bottom flange of the joist without being in contact with it, a clear half-inch space being left for the passage of the cold air."

The lintels are about 9 in. wide and 5 in. deep, and are grooved underneath, so that plaster will key into them and adhere properly.

The following table gives the size and weight of joists for various spans and loads, all joists being fixed 2 ft. apart from centre to centre:—

TABLE XXVIII.—STRENGTH OF JOISTS USED IN FAWCETT'S FIREPROOF FLOORS.

	Joists.		Safe Working Load per sq. ft. for different spans—								
	Size in ins.	Weight per ft.	8 ft.	10 ft.	12 ft.	14 ft.	16 ft.	18 ft.	20 ft.	22 ft.	24 ft.
		lbs.	cwt.	cwt.	cwt.	cwt.	cwt.	cwt.	cwt.	cwt.	cwt.
Buildings of the Domestic Class.	4×2	7	2	$1\frac{1}{2}$	1						
	$4\frac{3}{4} \times 2$	8	...	2	$1\frac{1}{2}$	1					
	$5\frac{1}{2} \times 2$	10	...	...	2	$1\frac{1}{2}$	1				
	$6\frac{1}{4} \times 2\frac{1}{8}$	11	...	...	...	2	$1\frac{1}{2}$	1			
	$7 \times 2\frac{1}{4}$	14	...	...	...	...	2	$1\frac{1}{2}$	1		
	$8 \times 2\frac{1}{2}$	15	...	...	...	...	...	2	$1\frac{1}{2}$	$1\frac{1}{4}$	1
Buildings of the Warehouse Class.	4×3	12	4	3	2						
	5×3	13	5	$3\frac{1}{2}$	$2\frac{1}{2}$	2					
	6×3	16	...	5	4	3	2				
	$7 \times 3\frac{1}{2}$	19	...	...	5	4	3	2			
	8×4	22	...	...	...	5	4	3	2		
	$9 \times 3\frac{3}{4}$	23	...	...	...	...	5	4	3	2	

17 *and* 18.—*Homan & Rodgers's "Flat-Brick" and Tubular-Lintel Floors.*—In 1885 Homan & Rodgers patented their "Flat-brick Fireproof Floors," in which flat bricks about 12 in. by 6 in. by 3 in. rested upon the flanges of ⊥-irons 12 in. apart, which in turn were carried on the lower flanges of **I** joists about 4 ft. apart. Concrete was deposited on the bricks so as to cover the joists.

The disadvantage of this system was that the under side of the ironwork was unprotected, save by the ordinary plaster of the ceiling. They have therefore superseded this floor by another, in which hollow lintels, remarkably similar in principle to those in Fawcett's floor, are used, the lintels being of triangular section instead of curved.

19. *Willis & Astley's.*—Willis & Astley's "Fireproof and Ventilating Floor" is of quite recent invention, and consists of rolled **I** joists 2 ft. apart with ⊥-shaped fire-clay lintels carried between them. The flanges of the lintels pass under and protect the lower flanges of the joists. The webs of the lintels are of arched form, and on them thin sheet iron is laid, upon which concrete is deposited to the top of the

joists. The webs of the lintels are pierced, so that a current of air can pass freely through the floor; this can be turned to account for ventilating the room beneath. One disadvantage is that the webs of the lintels, which are notched on to the iron flanges, have to bear all the weight, not only of the concrete itself, but also of the floor-load between the joists.

20. *Corrugated Iron Centring.*—A recent patent consists in the use of a permanent centring of corrugated iron instead of fire-clay lintels, the corrugations being of dovetailed section for the sake of strength, and to afford a key for the concrete above and the plastered ceiling below.

Comparison.—Many other systems have been invented, some successful, many unsuccessful, but sufficient has been said to show the chief varieties of flat fire-resisting floors in which concrete plays an important part. With our present knowledge it is impossible to institute a comparison between the different floors as to strength and fire-resistance. A series of actual tests would have to be carried out before this could be done, but tests made in Berlin (in 1892–3), on several floors in use on the Continent, and actual fires in England, go to prove that floors of ordinary concrete and iron are more liable to damage by fire than are floors containing cement slabs or fireclay blocks below the concrete. On the other hand it must be stated that the "Monier" floor, which consists of "cement" surrounding a network of iron bars, was severely tested at Berlin, and came through the ordeal as well as any floor containing brick or other blocks, although at the crown the "Monier" arch was only $3\frac{1}{8}$ in. thick.

Girders.—Large floors will require to be divided into bays by girders, which must be protected by concrete or by fire-clay blocks (Fig. 44). Sometimes, to save height, angle-irons are riveted to the webs of the girders, and the floor rests on these.

Columns.—Iron or steel columns or stanchions are now usually protected from fires, sometimes by means of special bricks filled up with fine concrete, or by concrete alone.

In the latter case, a key for the concrete is obtained by securing to the columns, with wire, vertical strips of iron corrugated horizontally. A mould of proper size is then placed around the column, and filled with concrete which passes into and is held by the corrugations. The strips of iron are sometimes omitted, but it is better to use them as they afford a key for the concrete. The thickness of concrete intended to protect iron columns, should never be less than 2 in., but ought as a general rule to be 3 in.

Since the first edition of this book was published, the use of concrete reinforced with iron has been largely extended, and some of the most important methods of construction will be considered in Chapter XXVI.

CHAPTER XXII.

CONCRETE ARCHES,—FLOORS, BRIDGES, SEWERS, &c.

Comparison of concrete arches and lintels—Mr. Colson's tests (Table XXIX.)—Deductions—Arches economise material—Approximate strength of floor-arches—Systems: 1. Homan and Rodgers's arched floor, 2. Moreland's, 3. Dennet and Ingle's—Abutments of floor-arches—Arches suitable for corridors—Girders and their protection—4. Lindsay's skewback girder and arch with trussed rods—Depositing concrete in arches—*Pro* and *Con.*—Ceilings—5. Arch-block floors—6. The "Monier" system (floors, domes, and bridges)—Domed ceilings, &c.—Bridges—Sewers—Drain-pipes, &c.

COMPARISON OF CONCRETE ARCHES AND LINTELS.—The compressive resistance of concrete so largely exceeds its tenacity, that it is, as we have already shown, little adapted for use in the form of flat lintels or slabs subject to transverse stress. It is much more economically used in an arched form, where it is subject as much as possible to a compressive stress. Indeed, it is probable that a lintel with fixed ends, contains within it, as it were, a hidden arch, and that it would be quite as strong or stronger if the lower segment, extending from the underside of the bearing at each end up to one-half the thickness of the concrete at the centre of the span, were omitted. Such is probably the case, but sufficient experiments have not yet been made to settle the point definitely. The following extract from *The American Architect* supports this theory, and deserves consideration.

"Some interesting experiments on concrete arches were made recently, during the construction of the new railway station at Erfurt. Some of the rooms were to be covered with concrete floors, carried on iron beams, while others, of

smaller size, were intended to be spanned by arches extending from wall to wall. One of the latter, something over seven feet in width, was covered with concrete, flat on top, and forming on the underside a segmental arch, the thickness of the material at the crown of the arch being four inches, and about eleven inches at the springing. The concrete was made of "Germania" Portland cement, mixed dry with gravel, moistened as required, and well rammed on the centring; and skewbacks were cut in the brick walls at the springing line, extending two courses higher, so as to give room for the concrete to take a firm hold on the walls.

"Fourteen days after completion, this floor was loaded with bricks and sacks of cement to the amount of more than six hundred pounds a square foot, without suffering any injury, although, after the load was on, a workman hammered with a pick on the concrete close to the loaded portion, so as to provoke the cracking of the arch if there had been any tendency to rupture. In the other cases, the concrete arches being turned between iron beams, the strength of the floor was limited by that of the beams, so that the extreme load could not be put on; but the curious fact was established that a section of concrete flat on top, and forming a regular segmental arch beneath, was far stronger than one in which a portion of the under surface was parallel to the upper, showing, apparently, that the arched form, even with homogeneous concrete, causes the conversion of a large part of vertical pressure into lateral thrust, reducing by so much the tendency of the load to break the concrete transversely.

"This observation is important theoretically as well as practically. It has been of late generally maintained that a concrete arch is not an arch at all, but a lintel, without thrust, and that the common form, flat above and arched beneath, is objectionable, as it gives least material at the centre, where a lintel is most strained. The Erfurt experiments directly contradict this view, and it remains for some students of architecture to render the profession a service by repeating them, and at the same time, actually deter-

mining the thrust, for a given load, of arches of particular forms. Until this is done the concrete construction, which is likely we hope to become before many years the prevailing one in our cities, will be practised with difficulty and uncertainty, if not with danger."

Mr. Colson's Tests.—The experiment by Mr. Colson, mentioned on p. 196, showed that the lower half of a concrete lintel with fixed abutments, cracked right across long before the upper half yielded. It is evident, therefore, that some portion of the lower half was mere useless dead weight and detracted from the load-carrying capacity of the beam. This portion is approximately shown in Fig. 9, by the dotted line *abc*.

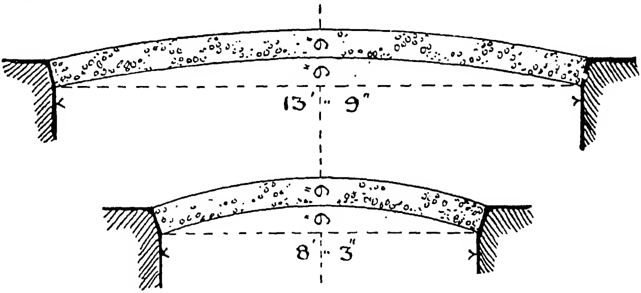


Fig. 42.—Arches tested by Mr. Colson.

Other experiments by Mr. Colson are recorded in the *Proceedings of the Institution of Civil Engineers*, Vol. LIV. (1877–8, part iv.). Six concrete arches of a uniform width of 21 in. and thickness of 9 in., with radial abutments as shown in Fig. 42, were made and loaded until they broke. Flat lintels of similar composition were also tested, and the results showed conclusively the immense superiority of the arched form, even when the rise of the arch was only one-eleventh or even one-eighteenth of the span. The concrete contained too much aggregate and far too much sand to give really good results, but this does not vitiate the comparison between the several tests. Others of Mr. Colson's tests of concrete lintels, besides the following No. 8, have been given in Table XXII. (Nos. 24 to 26), p. 191.

TABLE XXIX.—STRENGTH OF CONCRETE ARCHES, &c., TESTED BY MR. COLSON.

	Composition.			Age in Days.	Size of Arches.				Loaded on	Breaking Weight.	Reduced to B. W. at Centre.	Half W. of Slab.	Total Central Load.	Beam-Constant.†
	Portland Cement.	Sand.	Aggregate.		Breadth	Thickness.	Clear Span.	Rise.						
					ins.	ins.	ins.	ins.		cwt.	cwt.	cwt.	cwt.	
1	1	3	6 screened shingle	23–25	21	9	99	9	Central 18 ins.	110	100	6·6	106·6	1·16
2	1	3	"	28–31	"	"	"	"	"	135	122·7	"	129·3	1·41
3	1	3	"	21	"	"	165	"	"	90	85·3	11	96·3	1·75
4*	1	3	"	28	"	"	"	"	"	62·8*	59·5	"	70·5	1·28
5	1	3	6 broken brick	"	"	"	"	"	"	135·4	128·3	10	138·3	2·51
6	1	3	"	"	"	"	"	"	"	141·2	133·3	"	143·3	2·60
7 A	1	3	6 screened shingle	30	"	"	99	A	"	25·8	23·45	6·57	30	1·31
8 B	1	3	"	28	"	"	"	B	Central 6 ins.	5	4·85	"	11·4	1·00

* An excess of water was purposely used in mixing the concrete of this arch, and the resultant delay in setting is evident.

† Obtained by considering the arches, Nos. 1 to 6, as beams 18 in. deep (*i.e.*, 9 in. rise × 9 in. thickness), with fixed ends, and working out according to formula III., p. 194 ; No. 7 is calculated by the same formula as a beam with fixed ends, and No. 8 by formula I., as a beam with supported ends.

A. A flat lintel with abutments, forming therefore a "flat arch." Constant calculated by formula III.

B. A flat lintel merely *supported* at the ends. Constant calculated by formula I.

Deductions.—These experiments are extremely valuable, although they are not sufficient to settle definitely the relation between the strength of arches and lintels. It is remarkable, however, that, if the arches are considered as beams with a depth equal to the vertical distance from the level of the springing to the crown of the arch, they yield constants practically identical with the constant deduced from a flat beam of similar composition with fixed abutments. This may be merely a coincidence, but it is at any rate worth consideration. If the tests of the arches Nos. 1 and 2 be compared with that of the lintel No. 7 in this way, the two former being considered as fixed beams 18 in. deep, and the last as a fixed beam 9 in. deep, the resultant co-efficients are as nearly equal as possible. The arch No. 3, which is of larger span, gives a higher constant, while No. 4, in which too much water was used, is by chance again identical with No. 7.

The constant of beam 7 with *fixed* abutments has already been commented upon, on account of its increase over that deduced from beam 8 with *supported* ends, and it has been pointed out that this may be due to the formation, within the mass of the former, of what may be termed a hidden arch.

Arches Economise Material.—The great point to be considered respecting arches and lintels is that a given quantity of material used in an arched form is far stronger than the same quantity used as a lintel or beam. In other words, with the same dead weight, there is a far greater load-carrying capacity. Arches therefore are, strength for strength, considerably more economical than flat lintels or slabs.

For instance, each arch 1 and 2 contains the same amount of material as the flat lintel 7; but the total depth of each is double, namely, 18 in. instead of 9 in. The strength of *beams* varies as the square of the depth, and therefore a beam 18 in. deep will carry four times as much as one only 9 in. deep. Curiously, as we have already said, the arches 1 and 2 are almost exactly four times the strength of the

lintel 7. An arch equal in strength to the latter might have been made with only one-half the material.

APPROXIMATE STRENGTH OF FLOOR-ARCHES.—Until further experiments have been made, the nearest simple approximation to the strength of concrete arches of small rise (not exceeding, say, one-tenth of the span), will be to consider them as fixed beams, having a depth equal to the rise of the arch *plus* the thickness of the concrete at the crown.

This can only hold true of arches up to an unknown limit of rise. What this limit is, can best be decided by experiment. The tests under consideration were upon arches with rises of one-eleventh and one-eighteenth of the span respectively. The rise of floor-arches is usually about one-tenth or one-twelfth of the span, and the rule may therefore be taken to hold good in ordinary cases.

The thickness of the concrete must also be considered. In these tests, the thickness of the concrete was equal to the rise of the arch, and deductions from them can only fairly apply to arches in which the same proportion is observed. Usually the concrete is thinner at the crown than this proportion would give, but it should seldom be less for floors than two-thirds the rise.

1. *Homan and Rodgers's Arched Floor.*—One of the earliest patents for arched concrete floors was taken out by Homan and Rodgers in 1865. It consisted simply of rolled iron joists or girders about 10 ft. apart, with concrete arches springing from the bottom flanges. The underside of the flanges was not protected in any way. The upper surface of the floor was flat.

2. *Moreland's.*—Moreland's floor consisting of iron girders with a permanent arched centring of corrugated iron rising between them and covered with concrete, has already been mentioned. This has the advantage of doing away with the temporary scaffolding and is still sometimes used, but for spans of more than 6 ft. it will often be necessary to prop the metal, to prevent sagging during the ramming of the wet concrete.

3. *Dennet and Ingle's.*—Dennet and Ingle's floor has been

in use for a great many years. It is practically tne same as that of Homan and Rodgers, with the exception that the concrete has plaster of Paris for its matrix instead of Portland cement. The arches are made up to spans of 10 or 12 ft. and have a minimum rise of 1 in. to every foot of span. The upper surfaces may be either arched or flat, and the ceilings may be formed by plastering the arched soffits, or by fixing ceiling-joists beneath the concrete and plastering under them. See Fig. 43.

ABUTMENTS OF FLOOR-ARCHES.—The ends of arched concrete floors sometimes merely rest on corbel courses as shown in Fig. 43. Frequently, however, a chase, 4½ in.

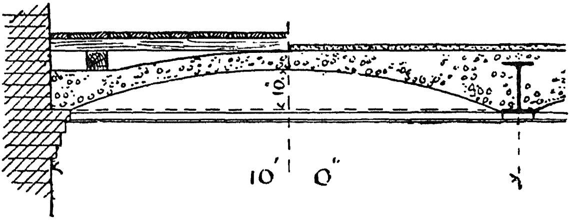


Fig. 43.—Dennet and Ingle's Arched Concrete Floor.

deep from the face, is formed in the wall, bricks laid in sand being built into the chase and removed immediately before the concrete is deposited.

A combination of the two methods is often adopted, *i.e.*, a shallower chase (say 2¼ in.) is formed in the wall immediately over a corbel-course of about the same projection. This can be utilised for 9 in. walls. An illustration of this method is given in Fig. 29, page 264.

ARCHES SUITABLE FOR CORRIDORS.—For corridors, up to 10 or 12 ft. wide, the arched system is particularly to be commended. No ironwork whatever is required, and the ceiling underneath can be finished in Keene's cement directly upon the concrete. The arched form of the ceiling improves rather than impairs its appearance, and the corbel-courses can be of moulded brickwork, or can be covered with plaster cornices as desired.

Girders and their Protection.—In large rooms, however, it is necessary to divide the floor into bays usually about 10 ft. wide or less, by means of iron or steel girders, and these are a source of weakness during conflagrations unless they are protected underneath. The bottom flanges of the girders were at one time invariably, and even to-day are frequently, left bare, but this ought not to be allowed.

A simple mode of protection is to surround them entirely with concrete, which should be not less than 2 in. thick. This is effected by keeping the temporary centres the

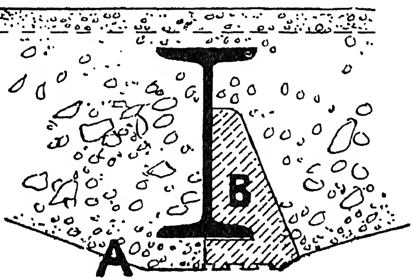


Fig. 44.—Girder protected by Concrete and Fire-clay Block.

necessary distance below the girders and ramming the space full of good fine concrete. This system is shown at A in Fig. 44.

Another arrangement is shewn at B and consists in the use of hollow or solid fire-clay blocks, grouted with cement, which protect the girders and form skewbacks for the springing of the arches. These add to the expense, but afford effective protection from fire.

4. *Lindsay's Skewback Girder, &c.*—W. H. Lindsay, Neal & Co. manufacture a special skewback girder, as shewn in Fig. 45, for arched concrete floors. The girders are entirely encased underneath with concrete. The illustration shews also the trussed rods, which this firm introduces to strengthen the floors and to prevent the concrete

collapsing under a sudden strain. An arch of this kind 6 ft. wide and 18 ft. span is said to have been "loaded in the centre with 7 tons without producing the slightest crack or discoverable flaw." This was equal to a distributed load of 14 tons, *i.e.* 2·6 cwt. per sq. ft.

The dimensions of several arched concrete floors were given in Table XXVI., page 261, and an example of groined concrete floors was illustrated and described on pp. 228—231.

DEPOSITING CONCRETE IN ARCHES.—A point of particular importance should be observed in the construction of concrete arches, and that is that the concrete should, wherever possible, be deposited over the whole span and of the full

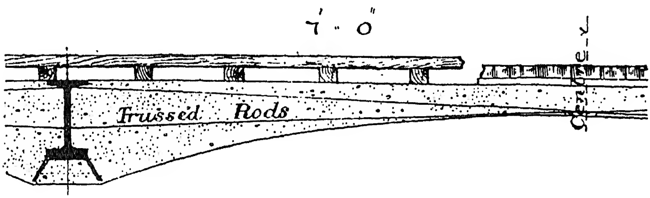


Fig. 45.—Lindsay, Neal, & Co.'s Skewback Girder and Arched Concrete Floor with Trussed Rods.

thickness at one operation. When this cannot be done, the full *thickness* must be deposited at once, commencing at the springing and finishing with a joint radiating from the centre of the arch. In other words, each "dump" of concrete must be regarded as the voussoir of an arch, and must be deposited accordingly. Concrete in arches must *not* be deposited in horizontal layers. We have already explained that there is a weak plane between every layer of concrete, a sort of plane of cleavage, and unless this is radial to the arch it is a source of weakness. Such joints have been the cause of more than one failure.

PRO AND CON.—The chief consideration in favour of arched concrete floors is that they are economical, all iron being omitted except the girders, and the concrete being cast

into the form in which it is capable of bearing the greatest load. But, when flat ceilings are required, this gain is counter-balanced by the excessive depth of the floor, which necessitates a greater height of walling; thus, an arched floor 10 ft. span, including (say) wood-blocks and the flat ceiling, would be 16 or 18 in. deep. It must not be forgotten, however, that most of the *flat* fire-proof floors require, for large spans, girders at intervals, and if the ceiling were formed under these so as to be quite flat, the depth would be as great as that of the arched floor, or even greater, for in many cases the flat floors rest on the top flanges of the girders, while arches rest on the bottom flanges and only just reach above the top ones.

Ceilings.—Flat ceilings can be formed under arched floors when necessary by hanging under the girders wood or light iron ceiling-joists, to which wood or metal lathing can be attached as shewn in Fig. 43, p. 291. These can then be plastered in the ordinary way. Instead of lathing and plastering, fibrous plaster slabs are sometimes used. Flat ceilings have the advantages of giving a slight further protection to the girders and of forming an air-space, which assists in deadening sounds, and gives room for pipes, ventilation, &c., but they waste a considerable amount of height.

5. *Arch-Block Floor.*—In America hollow concrete blocks have been used for fire-resisting floors. The floors of the offices of the *New York Tribune* were constructed by the New York Fire-Proof Building Co., with iron girders 6 ft. apart, between which flat arches were formed with hollow concrete blocks about 9 in. thick, 12 in. long, and of various widths (average width about 10 in.). The blocks were made from "plaster of Paris, coke-dust, and a peculiar quality of lime obtained only at Teil in France."* They could be cut with a hatchet, and holes were easily formed in them. It is said that blocks have been heated to redness and thrown suddenly into cold water without injury.†

* See Table XII. p. 89.

† *The British Architect*, July 14, 1876, report of paper read by Mr. James Montgomery before the *Liverpool Architectural Society*.

Several kinds of fire-resisting floors consist of arches of hollow fire-clay blocks or bricks, covered with concrete, but as the concrete in these plays quite a subordinate part, it is not within our province to describe them.

6. *The "Monier" System.*—A system of fire-proof flooring, which has had considerable success on the Continent, is that known as the "Monier" system. It consists of a network of wires embedded in concrete, but we have no details of the construction. Certainly floors formed on this principle are stated to be of quite startling thinness, some indeed not exceeding $1\frac{3}{4}$ inches.

A short time ago an attempt was made to float a company for working the Monier patents in England, but apparently without success. From the prospectus we learn that arched floors have been constructed of the following dimensions :—

1. Factory,	12 ft.	span	and	2	in	thick.
2. Brewery,	18 ,,	,,	,,	3	,,	,,
3. Warehouse,	19 ,,	,,	,,	3	,,	,,

The haunches were partially filled up.

But even more surprising results are obtained in other branches of construction. Three domes have been erected, at a brewery, 24 ft. 4 in. in diameter, 21 ft. high and only $1\frac{1}{2}$ in. thick, and another dome, 57 ft. in diameter and 32 ft. high has been erected on this system, and filled in between the ribs with glass.

Of bridges three examples are mentioned, the *first*, at Wildegg, 120 ft. span and 8 in. thick at the crown, according to one page of the prospectus, and 130 ft. span and only 6 in. thick according to another page; the *second* a railway bridge at Lisenbahn, 150 ft. span and $17\frac{1}{2}$ in. thick, and the *third*, a foot-bridge at Bremen, 125 (or 130) ft. span and $7\frac{1}{2}$ (or 8) in. thick.

In conclusion we may add that *flat* floors 13 ft. square and only 2 in. thick are said to have been erected *without iron beams*. For additional information, see Chapter XXVI.

Certainly the "Monier" system gives wonderful results

as far as strength is concerned, but there is just a question whether sufficient protection is afforded to the iron wires (on which the strength of the structure seems mainly to depend) by the very small amount of concrete with which they are covered.

The Builder of July 29, 1903, contains an article on the results of some tests carried on at Berlin in 1892–3 on the strength and fire-resistance of various so-called "fire-proof floors." A "Monier" floor with arched soffit and flat top consisting of "cement with a framework of wrought iron bars of about $\frac{1}{4}$ in. in diameter," was among those tested. It had a clear span of about 12 ft. with a thickness at the springing of about 15 in., and at the crown of only $3\frac{1}{8}$ in. It was subjected for an hour to a fire having an average temperature of about 1800° F. and was also loaded with about $4\frac{3}{4}$ cwt. per sq. ft.† "No appreciable damage was done, and the assessors were able to express their confidence and entire satisfaction by reporting the exhibition to be 'thoroughly fireproof.'"

DOMED CEILINGS, &c.—Domed ceilings are often constructed of concrete, and as these have little or nothing to carry besides their own weight, they can be made considerably lighter than floors of the same span. Thus, the semicircular dome, forming the ceiling of the "Cabinet Council Room of the New Foreign Office," is 36 ft. in diameter and only 9 in. thick even at the haunches. The coved ceiling over the ladies' dressing room at Her Majesty's Theatre was 30 ft. by 20 ft. and 5 ft. high, with a thickness at the springing of about 12 in. and on the flat soffit of about 9 in. Both were erected by Dennet & Ingle, and were described by Mr. J. J. Webster in his paper on "Fireproof Construction," printed in the *Proceedings of the Institution of Civil Engineers*, Vol. CV. (1890–1, part III.). For a description of the concrete domes at the new Roman Catholic Cathedral, Westminster, see p. 301.

External domes are sometimes built with a framework of iron, embedded in concrete, and may be finished outside with lead, copper, &c.

† 2613 kilogrammes per sq. mètre.

Concrete has frequently been used for filling up the haunches of stone or brick vaults, but it might also be economically substituted for the filling of stone or brick between the ribs of Gothic vaulting.

The use of concrete arches is not confined to floors and ceilings. They have been adopted frequently for large sewers and conduits, and also for bridges and other purposes.

BRIDGES.—At the Croft Granite Brick and Concrete Works, near Leicester, there are several arched bridges built of granite-concrete. One has a span of nearly 30 ft. and two others are each about 30 ft. wide with the main arch of 22 ft. span and smaller arches at the sides. The thickness at the crown is about 14 in. These have been built 3 or 4 years, and are as perfect as the day the centres were struck. One of them is subjected to the heavy moving loads of a railway engine and loaded trucks, but has shewn no signs of yielding.

The composition of the concrete for these bridges is 1 part Portland cement and 8 parts syenite crushed to pass a $1\frac{1}{4}$ in. ring. But in addition to the crushed material, lumps of syenite from 4 in. to 9 in. in length were carefully packed into the work, the several pieces being separated by 2 or 3 in. of concrete. In this way the proportion of cement to syenite was reduced from 1 to 8 to about 1 to 16. The concrete is far from homogeneous; the soffits of the arches, which remain as they were left by the centres, present a rough honeycombed surface, but, notwithstanding this, the aggregate seems firmly bound together.

Two of the arches have ornamental sham voussoirs and keystones of concrete affixed to the faces, and have also enriched panels in the spandrels, some of the panels having a red ground. Ornamental parapets complete the structures.

In two of the bridges, their exposed faces have been rendered, and grey and pink syenite, crushed into pieces of the size of peas or haricot-beans, have been mixed with cement and applied as rough-cast. The effect is pleasing.

A much larger bridge than any of these has been erected near Erbach, a station between Ulm and Friedrichshafen, It has a span of 95 ft. and a rise of 13 ft. The concrete is 1 ft. 7¾ in. thick at the crown and 2 ft. 3½ in. at the springing, and consists of 1 part Portland cement, 1 part sand, and 3 parts carefully washed and screened Danube gravel varying in size up to the size of walnuts. It was well rammed in radial layers 2 ft. 7½ in. wide. As the ground on which the piers were built was somewhat treacherous, it was thought that a homogeneous rigid structure would be liable to crack through unequal settlement. Asphalt layers were therefore inserted at the two abutments, and also at the crown of the arch. The Munderkingen Bridge, Württemburg, erected in 1893, has a clear span of 164 ft. and a rise of 16½ ft. Steel pivots are used in the abutments and crown, and the concrete is 3 ft. 3 in. thick at the crown, 3 ft. 8 in. at the springing, and 4 ft. 3 in. at the haunches.

Sewers.—Concrete has been largely used in the construction of sewers both at home and aboard. More than 20 years ago there were in London, south of the Thames, more than a mile and a quarter of sewers constructed entirely of concrete, and rather more than a mile constructed of concrete but lined with a 4½ in. ring of brickwork.

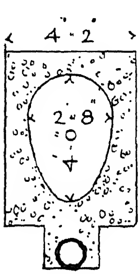


Fig. 46.—Concrete Sewer.

Fig. 46 is a section of the all-concrete sewers, and Fig. 47 of the larger sewers lined with brick.

Mr. Grant's specification* for these sewers required the concrete to have 3 bushels (about 4 cub. ft.) of Portland cement to 1 cub. yd. of sand and ballast; the centres were to be covered with sheet iron, copper, or zinc, and greased if necessary, to insure a smooth surface; the inverts below the springing were "to be rendered with Portland cement and sand, in equal proportions, and finished off

* *Proceedings of the Inst. C. E.*, vol. xxxii. (1870–1).

½ in. thick with a smooth trowelled face," done by a plasterer; the concrete for the arches had to have cement and sand next the face so as to avoid a rough finish, and all flaws found on removing the centres were to be touched up by a plasterer.

At Buenos Ayres there were in 1880 no less than 11 miles of concrete conduits varying from 12 ft. by 14 ft. down to 7 ft. in diameter, 12 miles of intercepting sewers from 7 ft. to 3 ft. in diameter, and 20 or 30 miles of egg-

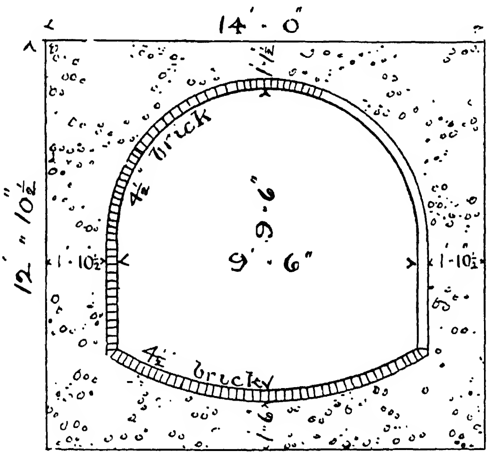


Fig. 47.—Concrete Sewer lined with Brick.

shaped collecting sewers from 4 ft. to 2 ft. 6 in. in width. For the last, the concrete was about 6 in. thick, and for the largest conduits it was only 14 in. thick.

It is scarcely within our province to enter into details of the mode of construction, as sewers of this kind are rather engineering than architectural problems.

DRAIN-PIPES, &c.—Drain-pipes are now made of concrete in considerable quantities by several firms. The Imperial Stone Company's pipes ~~are known as~~ "Silicated Stone Pipes."

They are made in sizes from 6 to 36 inches in diameter, but the largest sizes are perhaps the most useful. They are quoted at from 6*d.* to 10*s.* per linear ft. according to the size. The concrete is well tamped or rammed by machinery as the mould is filled. The thickness of the rim is about one-twelfth the diameter of the pipe. The ends are not provided with a projecting socket as in the case of earthenware drain-pipes, but have a bevelled edge at one end with a corresponding recess at the other. This leaves the outside of the pipes quite straight. They are not burnt like ordinary pipes and are therefore not warped. This trueness of line allows them to be laid very regularly.

Some tests reported in *The Builder* for April 1, 1882, showed that "Silicated Stone Pipes" were about 35 per cent. stronger than ordinary stoneware pipes.

Less cement is required to fill the joints of the former than of the latter, as the spigot and socket of the concrete tubes can be made to fit accurately, while the sockets of stoneware pipes must be made large enough to allow for a certain amount of twisting in the kiln.

It has been said that sewage may have an injurious effect on the concrete, but this opinion does not appear to have been corroborated by actual experience. About fifteen years ago, however, at Bournemouth, concrete pipes were found to vary considerably in serviceableness, some of them being very porous. There need be no fear of porosity, if the pipes are properly made, the concrete being mixed with the full quantity of water and well rammed.

Ordinary drain-pipes, when passing under buildings or through soft ground, ought to be entirely surrounded with concrete not less than 6 in. thick in any part, *i.e.* a 4 in. pipe would be embedded in the middle of a mass of concrete about 18 in. square, a 6 in. pipe in concrete about 20 in. square, and a 9 in. pipe in concrete 24 in. square. A slab of the proper width and 6 in. thick is first deposited; the pipes are then laid, and after being tested are surrounded with the rest of the concrete, which should be carefully rammed under the pipes. Another and perhaps better

method is to lay the pipes on small piers of concrete or brick, and, after testing them, to fill entirely around them with concrete. Soft places in the ground under drain-pipes should be excavated and filled with concrete, which may be of a coarser kind than that required for bedding around the pipes.

The construction of sewers, conduits, bridges, &c., in re-inforced concrete, will be described in Chapter XXVI.

Concrete Domes.—In the new Roman Catholic Cathedral, Westminster, designed by the late J. F. Bentley, concrete has been freely used in arches and domes. The principal domes over the nave have a diameter of 60 ft. and a rise of 20 ft. 6 in. The intrados has a radius of 31 ft. 6 in., and the extrados a radius of 34 ft. 1 in. The thickness of the concrete at the crown is 13 in., and increases gradually from this to 18 in. at a diameter of 44 ft., and to 3 ft. at the springing.

CHAPTER XXIII.

ROOFS AND STAIRS.

Flat roofs—Prevention of cracks—Condensation—Protection during setting—Sloping roofs—Preferability of flat roofs—Roofing slabs and tiles—Stairs.

Flat Roofs.—Concrete roofs are now coming somewhat largely into use. In large towns, many buildings are erected with flat fire-resisting roofs, which are not only economical in construction, but also provide an area adapted for a variety of purposes, such as exercise, drying clothes, and even the growth of plants.

Any of the systems of flat or arched floors already described, may be used for roofs, but some differences in detail will be necessary, as provision must be made for rainfall and also for the contraction and expansion, which, in the case of slab-floors of considerable span, would tend to crack the concrete through the extremes of temperature to which they would be subject.

The necessary falls and gutters can be formed by means of an inferior concrete laid on the top of the roof proper. The whole should then be covered with a coat of good asphalt, such as Claridge's or Val de Travers, and the flashings from the roof to the parapet can be formed with the same material. The asphalt should not be less than $\frac{3}{4}$ in. thick, and for inferior material 1 in., and should be applied in two layers breaking joint, the concrete having first been rendered with cement-mortar. For roofs designed for use as drying or airing grounds, the asphalt should be thicker and finished with fine grit.

Prevention of Cracks.—In order to prevent cracks being

caused in the concrete by changes of temperature, it is customary to divide it into separate slabs of moderate size. All roofs of considerable area will be divided by main girders every 10 or 12 ft. or thereabouts, and the separation of the concrete (when this is laid over the top of the girders) can best be effected by means of a strip of wood about ½ in. thick placed along the centre of each girder; the strip may extend the full thickness of the roof, and will form a guide for the workmen in depositing the concrete. Sometimes, however, the joint extends through only one-half the thickness. When the concrete has set sufficiently, the wood can be picked out to the depth of 1 in. and the joint filled with mortar or, better, with asphalt; the whole roof can then be finished with asphalt. When the concrete rests on the lower flanges of the girders, and is therefore divided by them into distinct masses, no further precautions need be taken against contraction.

CONDENSATION.—There is some danger of moisture condensing on the underside of solid concrete roofs, and for this reason and also to insure a more equable temperature, a separate ceiling is sometimes provided underneath. This can be formed by wood or light iron ceiling joists, carried by the main girders and finished with wood or metal lathing and plaster.

PROTECTION DURING SETTING.—In laying flat slab-roofs especial care should be taken to prevent loss of moisture during the setting of the concrete, particularly in warm dry weather. This can be done by covering the concrete with water, or wet sand or sawdust, or in other ways as already indicated.

SLOPING ROOFS.—Where the usual sloping roofs are required to be fire-resisting, they can be constructed with iron principals carrying ⊥, L or I iron purlins 2 to 4 ft. apart. Between the purlins coke-breeze concrete can be laid, on which slates can be nailed without the need of wood laths. The concrete may with advantage be covered with roofing-felt before the slates are laid.

Domes and vaults of concrete have been constructed* with and without framework of iron, &c. Flat roofs are, however, cheaper, and it is easier to construct a *flat* fire-resisting roof than to protect from fire all the members of trussed roof-principals.

The Leland Stanford Junior Museum at Palo Alta, California, is built almost wholly of concrete, and has a sloping concreted roof, supported on trusses 10 ft. from centre to centre. The concrete roofing slabs are 10 ft. long and about 2 ft. 6 in. wide, the lower surface having a web in the centre and curving up on each side of this to the edges. A twisted iron rod is embedded in each web. The lower edge of each slab is rebated so as to overlap the upper edge of the slab below it about 2 in., and a strip of lead is inserted in each joint. The ends of the slabs are supported by the roof-tresses; a channel is formed in the concrete on each side of the joint over the truss, and the channels and joint are covered with concrete tiles, somewhat resembling in shape an ordinary ridge-tile. Similar tiles are placed at distances of about 2 ft. 6 in., for the sake of appearance.

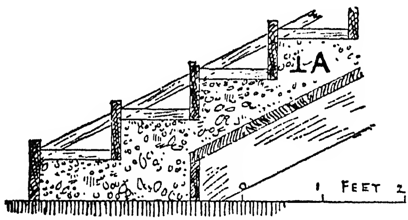


Fig. 48.—Concrete Stairs and Framing.

Roofing-Slabs and Tiles.—Concrete roof-slabs and tiles, grey and red, have been made by W. H. Lascelles & Co. and other firms, but have not come much into use, and concrete ridge-tiles and finials can also be obtained.

Thomann's Roofing Tiles are about 12 in. square, and are laid diamondwise, being secured to the laths by a lug descending from the upper corner of each. Wedges are driven between the lugs and laths, and by this means pro-

* See Table XXVI., p. 261, for vaulted roof of warehouse, &c., and p. 295 for domes on the Monier system; see also p. 301.

jecting lips along the underside of the two lower edges of each tile are drawn tightly against corresponding lips rising above the upper edges of the tiles in the course below.

Stairs.—Single steps of concrete or artificial stone can be obtained and built into walls, after the manner of stone steps, but this system partakes of the disadvantages of stone as the steps are liable to damage by fire, especially if they are merely built into the wall at one end.

A better method is to form the whole flight in one mass of concrete by means of framing, as shown in Fig. 48, the sides of the stairs being fixed in chases cut in the walls. By means of suitable moulds, the steps can be formed with moulded nosings, but it is usually preferable to have separate treads, so that when much worn, they can be easily replaced. The soffit can be made in steps if required, but the continuous slope is best and most easily formed. For stairs not more than 5 ft. or 6 ft. wide, fixed at both ends into walls, ironwork is not absolutely necessary, but for wider stairs the concrete should be reinforced, either as at A, or in some other way (see Chapter XXVI.).

For open-newel stairs, the free end ought to be strengthened by a rolled-steel joist, bolted at the top, to another joist extending along the free edge of the landing, or by a steel skeleton, consisting of raking piece, and upright and horizontal bars riveted to the shape of the steps. A close moulded outer string of reinforced concrete is often used to give strength to open-newel stairs.

Sometimes a network of iron bars and cross rods is used after the manner described for floors, and this method is to be recommended on account of its strength and the prevention of utter collapse in the event of a severe fire.

The treads can be formed with Hawksley's patent wood-block treads, Mason's "Unwearable" metal treads, or Doulton's silicon treads, &c., or, as is done in many parts of Spain, with tiles kept in position by a stout wood riser. The riser may be finished with cement, tiles, marble, &c. Or the treads and risers may be faced with wood, so that the stairs can scarcely be distinguished from an ordinary flight.

CHAPTER XXIV.

WALLS.

Pro and *Con.*—Cost—M. B. W. Byelaws—London C. C. Byelaws—Building-Frames—Concrete posts and slabs—Lascelles's slabs—Voids—Wood in concrete—Flues—Pipes—Absorbence and porosity—An angle-turret—Chimneys—Hollow walls—Thickness of walls—Retaining walls, Formula XIII. (Table XXX.)—Cracks—External treatment: 1. Facing-concrete, 2. Rough trowelling, 3. Stucco, 4. Colour, 5. Rough-cast, 6. Sgraffito, 7. "Half-timber" work, 8. Brick and stone, 9. Tiles, &c.

PRO AND CON.—The use of concrete for the walls of buildings has not extended as rapidly as was anticipated by men who wrote and spoke about the material twenty or thirty years ago. Several causes have combined to hinder architects from adopting it. Notably among these are the dangers arising from its manufacture by careless workmen and unscrupulous contractors, the difficulty and expense of moulding it to curved or irregular forms, and the bald appearance and unlovely colour of the material itself.

The erection of a concrete building is an event requiring a fresh study of nearly every detail. The insertion of brick or stone quoins and window dressings, or of projecting features of any kind, is fraught with difficulty. The points of attachment for joinery, &c., must be considered before the walls are begun. And in a hundred ways thought must be exercised or the building may prove more or less a failure.

Other objections to concrete walls are their homogeneity and hardness, which render the hanging of pictures and the fixing of plugs difficult tasks, and which make alterations a costly affair (this last is raised as an objection sometimes, but may perhaps be regarded as an advantage). The case with

which sound is transmitted through concrete walls is certainly a point against them. But it may be said, on the contrary, that good concrete is considerably less pervious than brickwork and some kinds of stone, stronger and more durable, and, under certain circumstances, much cheaper.

COST.—The matter of cost, however, is one which cannot be settled off-hand; so much depends upon the distance which brick or stone, or, on the other hand, the concrete materials, may have to be brought, and upon the price of these materials; upon the cost of skilled and unskilled labour; upon the simplicity or complication of the plan of the proposed building, and the detail of its elevations, and so on. At one time, it was customary to talk volubly of the great economy of concrete over brickwork or stonework, but over and over again contractors have shown by their tenders that they have thought quite otherwise.

Engineers certainly find it economical to employ concrete for marine-walls, breakwaters, dock-walls, and the like, but these are vastly different from the walls of buildings; the concrete is in large masses, and requires, in comparison with its bulk, very little framework, whereas in buildings the walls are thin, and the cost of the framework (including labour in fixing and removing), especially if the plan is irregular, amounts to a considerable sum per cubic yard. Again, on the sea-beach, engineers are provided with suitable sand and gravel or shingle, for the merely nominal cost of getting it; sometimes the aggregate required in buildings must be brought from a distance, and must be broken and washed before it is fit for use. Engineers, too, make use of a concrete in the backing of retaining-walls, and in the hearts of dock-walls, &c., much inferior in quality to that which is required in the walls of buildings; in those positions, 1-to-10 and 1-to-12 mixtures are far from un common.

M. B. W. BYELAWS.—Up to 1872 the Metropolitan Board of Works forbade the use of concrete for the walls of buildings, but in that year it was agreed to grant licences for its use on special application being made and under certain

conditions. In 1885, however, an action was brought against a builder, and it was decided by the magistrate that concrete walls did not contravene the byelaws of the Board, and therefore that special licences were not required. In consequence of this decision, byelaws to regulate the erection of concrete walls were passed and came into force in 1886. These byelaws have been modified (in 1891) by the London County Council.

LONDON C. C. BYELAWS.—The following are the byelaws now in force in the Metropolis :—

"Whenever concrete is used in the construction of walls, the concrete shall be composed of Portland cement and of clean Thames or pit ballast, or gravel, or broken brick or stone, or furnace clinkers, with clean sand in the following proportions, viz., one part of Portland cement, two parts of clean sand, and three parts of the coarse material, which is to be broken up sufficiently small to pass through a two-inch ring.

"The proportions of the materials to be strictly observed, and to be ascertained by careful admeasurement; and the mixing either by machine or hand to be most carefully done with clean water, and, if mixed by hand, the material to be turned over dry before the water is added.

"The walls to be carried up regularly and in parallel frames of equal height, and the surface of the concrete filled in the frame to be left rough and uneven to form a key for the next frame of concrete.

"The thicknesses of concrete walls to be equal at the least to the thicknesses for walls to be constructed of brickwork prescribed by the 12th section of the Metropolitan Building Act, 1855, and the first schedule referred to therein.

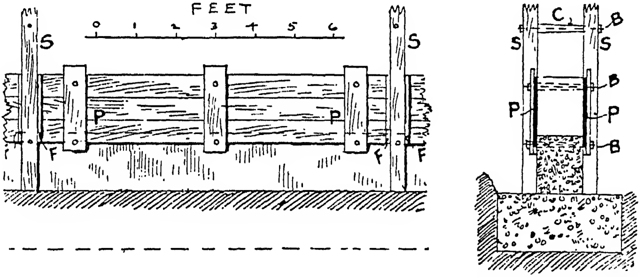
"Such portions of concrete party-walls and chimney-stacks as are carried above the roofs of buildings to be rendered externally with Portland cement."

The chief difference between these regulations and those previously in force is in the proportion of the ingredients. In the earlier regulations, the concrete might consist of one part of cement, and *eight* parts of sand and broken material, and these two might be measured together, so that really

the cement and aggregate would be in the ratio of about 1 to 11 if the ingredients were measured separately. The new regulations have made a startling change in this respect, insisting upon a ratio of 1 to 5.

Some needlessly detailed provisions about measuring the ingredients, grouting, flue-cores, &c. have been omitted in the new bye-laws. But strangely enough, the quality of the cement, which is really the most important consideration, is entirely neglected in the new regulations as it was in the old.

BUILDING-FRAMES.—In Chapter I., a short outline of the development of concrete building in England was given, and mention was made of several patents which had been taken



Figs. 49 & 50.—Elevation and Section of Building-Frame for Concrete Walls.

out for concrete-building appliances. Many of these have allen into desuetude, and others are not often used.

The principal parts of all building-frames for concrete walls are the "standards" and the "shutters" or movable panels. The standards are usually of wood, sometimes of iron, and are of any convenient length. We do not think it necessary to enter into the details of the different patented apparatus; it will be sufficient for us to explain the common system, which, after all, will usually prove best and most economical. See Figs. 49 and 50.

Standards, SS, are bolted together in pairs, the space between them being the thickness of the intended wall. These are then set perpendicular at distances of from 6 ft.

to 12 ft., according to the length of the wall. The standards at the angles of the building must be bolted together diagonally. All the pairs of standards are kept in position by means of stays nailed to stakes in the ground, or in some other manner, and are also tied together longitudinally by means of pieces of wood, such as slater's laths, nailed from pair to pair, on each side of the wall. Great care should be taken that the standards are perfectly perpendicular and in line, as on them the straightness of the future wall depends.

Sometimes the standards are omitted altogether, and the walls formed by means of panels only, but this enhances the difficulty of constructing the walls quite straight and vertical. A description of an apparatus of this kind is given on page 312.

The "shutters" or movable panels, PP, are usually made of 1 in. or $1\frac{1}{4}$ in. boards nailed to ledges along the back, and smoothly planed on the face. Sometimes thin sheet-iron is nailed on the face of the boards to protect them from the wet concrete, but this is scarcely necessary, as it increases the cost without corresponding benefit, and renders the panels more difficult to shorten or alter in any way.

To prevent the adhesion of the concrete, the faces of the panels are frequently covered with a coat of oil or soft soap. Cases have occurred in which soft soap used in this way has prevented the setting of the cement, but perhaps an excessive quantity was used. Sometimes crude petroleum is used instead of soap. The panels should be well cleaned immediately on their removal from the wall, and if this be thoroughly done, no further preparation need be made. When the concrete is to be faced with stucco or other material, a smooth face is neither necessary nor desirable.

The panels are, like the standards, bolted together in pairs by means of wrought-iron bolts, BB, passing through turned hardwood cores or distance-pieces, CC, which regulate the thickness of the wall; these cores are made to taper slightly, in order that they may be the more easily driven out when the concrete has set.

The width of the panels is usually such as to allow a

layer 18 in. deep to be deposited at one operation, but in exceptional cases they are made for the deposition of 24 in. layers.

When the standards are all in position, the panels are laid between them, and secured by means of fillets, FF, nailed to the standards. Panels should be provided sufficient to enclose the whole length of walling intended to be formed in one day, as otherwise the concrete will be strained by the removal of the panels in less than twenty-four hours. When some of the panels have been fixed in position, the concrete may be mixed, deposited within the frames to the full depth, and rammed, and so on, until the day's allotted task is complete.

When the circuit of the building has been made, work is recommenced at the same pair of panels as on the first day. These are removed by withdrawing the bolts; their faces are scraped clean of all cement, &c., and the panels are refixed on a higher level, the lower row of bolts in the panels now passing through the cores of the higher row in the previous layer. As the work proceeds, other panels are taken down and refixed until the second layer is complete. No panel ought to be removed in less than twenty-four hours, for Portland-cement concrete. The holes left after the cores are withdrawn must be completely filled with cement mortar (1 to 2).

Ransome's apparatus for solid concrete walls (Fig. 51) is simple and ingenious. Each shutter is formed of three boards $5\frac{3}{4}$ in. by $1\frac{1}{4}$ in., with 6 in. by $\frac{7}{8}$ in. by 16 in. ledges nailed on the back. A hole $\frac{3}{4}$ in. in diameter is bored through the shutter at the centre of each ledge. The standards are 3 ft. 6 in. long, formed with two side pieces $5\frac{3}{4}$ in. by $1\frac{1}{4}$ in., and two 3 in. by $\frac{3}{4}$ in. packings between the ends, so that a continuous slot, 3 ft. long by $\frac{3}{4}$ in. wide, is left between the side pieces. The shutters are set up in pairs (two shutters on each side of the wall), and are bolted together with $\frac{5}{8}$ in. bolts passing through the standards as shown. Each bolt is fitted at one end with an adjustable collar having a projecting lug, which is placed in the slot of the standard to prevent the turning of the bolt, and at the other end with a cast-iron washer and

hand-nut. When one layer of concrete has properly set, the lower bolts of the standards are withdrawn by means of a lever; the standards are then pushed up to the next row of bolts, and the lower set of planks is removed and set in place upon the upper set. The scaffolding and hoisting tackle are supported on reversed troughs, $5\frac{7}{8}$ in. wide by $5\frac{3}{4}$ in. deep, constructed of $1\frac{1}{4}$ in. boards, to which 2 in. by $\frac{3}{4}$ in. wrought-iron bands are screwed. These troughs are

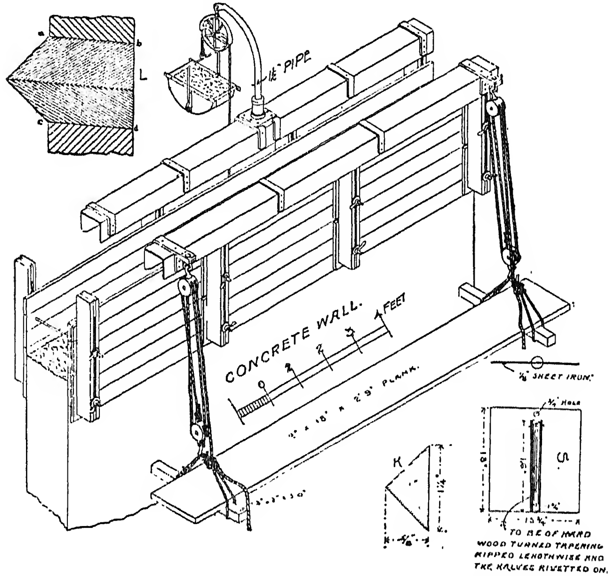


Fig. 51.—Ransome's apparatus for building concrete walls.

laid on the tops of the standards as shown. One of them is fitted with two rings, to which the blocks supporting the scaffold are attached; the other is fitted with a socket in which the crane-jib revolves. The concrete is hoisted in the iron bucket, which is 10 in. wide, 18. in. long by 9 in. deep (in the middle), and is swung on hooks and fitted with a latch so that the contents can be rapidly tipped between the shutters.

Recessed joints to imitate masonry are formed by means

of horizontal and vertical triangular fillets K nailed to the outer shutters. Where the edges of two shutters meet, the joint is formed as at L, the edges *ab* and *cd* being bevelled to prevent the edges of the planks from springing in. To prevent cracks in such walls, through-joints are formed at intervals from base to summit by means of sheet-iron plates S; each of these joints is arranged to fall on one of the lines of vertical-recessed joints, so that in the first, third and fifth courses the through-joint extends to the face of the wall. In the second, fourth and sixth courses, recesses $3\frac{1}{4}$ in. deep are formed opposite the through-joints by means of cores, and concrete blocks are afterwards inserted to match the other work, and to give the appearance of proper bond.

L-Shaped Tiles.—A writer in *Indian Engineering* has pointed out an ingenious but simple way of building concrete walls without shutters and frames. The invention consists in the use of terracotta or other tiles of L-shaped section, laid along the two faces of the wall, thus ∟ ⅃ ; the space between is filled with concrete, and another course of tiles is then laid to break joint with the course below; and so on. The faces of the walls are by this method finished in a durable manner; and the system has the further advantage of allowing the insertion of projecting features in any part of the building, without any of the difficulties which occur when shutters are employed. The Cockrill-Doulton patent tiles, which are now made by Messrs. Doulton & Co., are of this type.

Concrete Posts and Slabs.—At Croft one or two cottages, &c., have been built with square concrete uprights containing grooves, into which 2 or $2\frac{1}{2}$ inch concrete slabs (like flags) are fitted. The horizontal joints of the slabs are tongued and grooved. The houses are said to be comfortable, but it is not a system of building which can be recommended except for outbuildings.

Lascelles's Slabs.—Lascelles's system is applicable in country districts where bye-laws do not insist on solid walls. It "consists in fixing by nails or screws, through holes in each corner, thin slabs of very strong concrete on both sides of a skeleton wood partition, and finishing by a thin coat of

plastering," "Fish-scale slabs," 3 ft. by 2 ft., of a red colour are moulded on the face to imitate weather-tiling.

Voids.—In monolithic walls the openings of windows and doors, including the necessary reveals, must be formed with wood framing, which must be kept from bulging inwards by suitable struts. The temporary lintels must be supported on props, the props resting on wedges by which their removal is facilitated. The head of an opening may be chamfered by means of a triangular fillet, F, nailed to the outer lintel, L. Permanent lintels, either of wood, iron, or stone, or brick or stone arches, are unnecessary, but Mr. Potter recommends the insertion of wrought-iron bars (caulked at each end), a few inches over all openings, as these "help to prevent the unsightly cracks which sometimes occur in concrete walls."

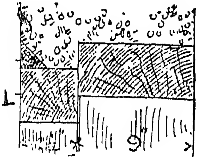


Fig. 52.—Temporary supports of chamfered head in concrete wall.

Wood in Concrete.—The insertion of wood bricks or bond-timber into concrete walls cannot be recommended, as they are sure to swell with the moisture, and may afterwards become loose, or eventually rot. It is always better to use breeze-bricks (made from Portland cement, coke-breeze, &c.), or Thompson's "Brickwood" fixing-blocks. These hold nails, and are not liable to swelling or decay, or to damage by fire. To prevent the ends of wood joists, purlins, blocks, &c., where such are used, from becoming loose after the concrete has dried, they are usually set with large nails, which are left projecting an inch or more, and so get a hold in the concrete. Or the ends of the joists can be built into earthenware or stoneware joist-boxes, which are embedded in the concrete. Or soft bricks can be built into the concrete where required to receive the joists, and when the concrete has set and the panels have been removed, the bricks can be cut out and the joists inserted. In many cases the upper walls are thinner than those below, and the joists can rest on plates laid on the ledges thus formed.

Flues.—Flues for smoke and ventilation may be formed

by wooden cores, which are made collapsible in order that they may be easily withdrawn. But it is always far better to form the smoke-flues by means of earthenware or stoneware pipes; these may be ordinary circular drain-pipes, socketed or unsocketed, or may be special flue-pipes of circular, elliptical, or oblong form, the oblong form having rounded corners. Combined smoke-and-air flues of various sections can be obtained from several makers, and these are well adapted for building into concrete chimney-breasts.

One of Benison's patent smoke-receivers may with advantage be built into the concrete over each fire-place opening. These are blocks of fire-clay, shaped like wide shallow keystones, and through each is a hole for the smoke, large at the bottom and tapering upwards to the size of the flue above.

Pipes.—Pipes for water, gas, waste-water, &c., should never be built into concrete walls, on account of the difficulty of repairing them in case of leakage. Chases can easily be formed in walls where required to receive such pipes, and the front of these can be finished afterwards with wood casing.

Absorbence and Porosity.—Good concrete is much less absorbent than ordinary bricks, while in brickwork there is the further disadvantage that the joints (if of lime-mortar) are easily penetrated by water. Bad concrete, however, cracks and admits driving ra: easily. Mr. Payne summed up the discussion which followed the reading of his paper on "Concrete as a Building Material," by saying, "Some five speakers have averred that concrete is wet, condenses water, shrinks, cracks, and contracts, while ten declare that it does not condense water, does not shrink, nor crack, nor take up damp."

Mr. Payne also wrote to a number of persons who had had a large experience in concrete building, and their testimony was to the effect (1) that concrete houses are warmer and drier than brick or stone ones, and can be sooner occupied; (2) that concrete does condense moisture (so also do brick and stone), but that plaster rendering inside overcomes the objection; and (3) that concrete

made with good air-slaked Portland cement does not shrink.*

AN ANGLE-TURRET.—An instance of concrete building was given by Colonel Lumsden in the same discussion. The walls of certain additions to his own house, an old Aberdeenshire castle, were built of concrete, 15 in. thick up to the first floor, and 12 in. above; at one corner a hanging turret about 6 ft. in diameter, was constructed with walls 9 in. thick, the supports under it being removed at the end of a week. The concrete was composed of one part Portland cement and six parts gravel, varying in size from a pea to a hen's egg, and was afterwards skimmed outside with a coat of cement mortar, $\frac{1}{8}$-in. thick (3 cement to 5 sand).

CHIMNEYS.—The chimney-stacks of concrete buildings and even chimney-tops are often formed of concrete, but it is always advisable to form the flues in concrete chimney-stacks with fireclay tubes in order to mitigate to some extent the great variations of temperature, which would cause contraction and expansion, and consequently cracks in the material. A still better course is to build the stacks entirely of brickwork.

Concrete has also been used occasionally for large chimneys from boilers. The material, however, does not appear to be able to withstand the severe heat of a chimney as well as good brickwork does, but cracks after a time. The first example in this country was designed by Mr. H. H. Wake, and built at Sunderland for the River Wear Commissioners. Its foundation was a bed of concrete 12 ft. square and 6 ft. thick, deposited on "made ground" consisting of sand and town-rubbish. The base of the chimney was 24 ft. 9 in. high, 7 ft. 6 in. square outside, and 4 ft. square inside, and lined with fire-brick. Above the base was a moulding 21 in. high. and from this rose an octagonal shaft 30 ft. high, 15 in. thick at the

* Apparently contraction during setting and hardening is here referred to; this must not be confounded with the contraction and expansion due to changes of temperature.

bottom, and 9 in. at the top. The concrete for the base consisted of 1 part Portland cement and 8 parts shingle and sand, that for the shaft of 1 part cement and 5 parts gravel and sand; rubble stones were also packed into the concrete as it was deposited. The chimney was finished externally with a $\frac{1}{4}$-in. coat of cement and sand (1 to 1), "divided into ashlar."*

HOLLOW WALLS.—Hollow concrete walls have frequently been built in order that the internal face of the walls may be perfectly dry, and of more uniform temperature. They may be formed by inserting in the required position between the shutters a 2 in. or 3 in. plank tapering slightly in thickness, from the top edge to the bottom; the taper facilitates the removal of the plank. When the plank has been withdrawn, metal ties are laid across the cavity, as in hollow brick walls, and on these ties the plank rests during the formation of the next layer. For wider cavaties, hollow cores or double shuttering may be used, and the two parts of the wall may be united at intervals by concrete withs, as shown in Fig. 64.

THICKNESS OF WALLS.—There is no doubt that good concrete walls are stronger than good brick walls; but such is the danger of concrete being scamped, that the regulations of the London County Council (mentioned above) require the thickness of concrete walls in buildings to be equal, at the least, to the thicknesses for brickwork prescribed in the "Building Act." Mr. Slater's opinion of monolithic concrete walls is that they "are really stronger than brickwork, drier and more cheaply built, but great care must be taken in the preparation of the concrete: the cement must be of the best, the aggregate must be broken to the proper size, and the whole thoroughly well mixed. If these precautions are taken, the thickness of the walls may be about twenty per cent. less than with brick" †

* Paper by Mr. R. M Bancroft, read before the *Civil and Mechanical Engineers' Society*, 1875.

† John Slater, B.A., in Carpenters' Hall Lecture on "Concrete," March 17, 1886.

SWIMMING-BATHS.—Concrete is now largely used for the walls and floors of swimming-baths. Fig. 53 is a section through the wall, floor, and gangway of such a bath. In this case a passage is shown around the bath under the gangway; this allows convenient access to the various pipes, &c. The gangway itself may be formed with a solid concrete floor or with iron or steel joists (resting on the bath wall at one end and in the wall of the building at the other) surrounded with concrete. This floor will give additional stability to the wall of the bath. The overflow water from the bath is shown to pass from the channel, which is built into the facing of the wall at A, by means of a pipe, into the concrete channel at B. The latter discharges into a manhole or intercepting trap outside the building.

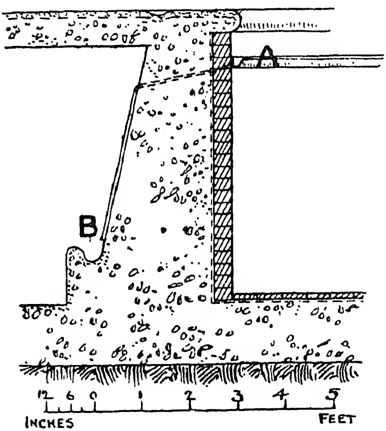


Fig. 53.—Section through Wall and Floor of Swimming-bath.

The concrete for the walls and floors of baths should be carefully proportioned so as to be as homogeneous as possible, and should be covered with a coat of cement mortar (1 to 1 or 1 to 2). After this has been done, the bath should be filled with water, and thoroughly tested as to its imperviousness. If this be perfect, the floor can be finished with strong glazed tiles, bedded in cement mortar and grouted, and the walls can be lined with single glazed bricks, also bonded with cement mortar and grouted. The thickness of the floor of the bath will depend largely on the nature of the ground; it ought to be strong enough

to prevent unequal settlement, as this might cause cracks in it and consequent leakage.

RETAINING WALLS.—Concrete is excellently adapted for retaining walls.* It may be used alone or in conjunction with a facing of stone or brick. The thickness of retaining walls varies not only according to their height, but also according to the nature of the ground behind them. The formulas usually adopted for calculating the strength of brick or stone walls may safely be used for concrete. The following constants and formula are extracted from Rivington's "Notes on Building Construction," Part IV., to which valuable work the reader is referred for further information.

The values of K and *w* are given as follows for different kinds of ground:

TABLE XXX.—CONSTANTS FOR RETAINING WALLS.

Nature of Ground.	K.	*w*.†
Sand dry and fine	·35 to ·40	[80]
wet	·44	[90—110]
very wet	·39	
Vegetable Earth dry	·41	90
dry and consolidated	·26	...
moist	·29 to ·26	...
very wet	·52	110
Loamy Earth dry and consolidated	·33	80 100
Clay dry	·41	...
damp, but well drained	·29	120
wet	·53	...
Gravel—clean	·27	[100]
containing sand	·44	112
Loose Shingle	·33	[100]

* See Fig. 58, p. 329.

† The values of *w* inserted in brackets are not given in Rivington's "Notes."

Let T = thickness of wall with both sides vertical,
H = height of the wall,
W = weight of a cub. ft. of the wall,
w = ,, ,, ,, ,, earth behind the wall.

Then *for walls with both sides vertical,*

$$T = K \times H \sqrt{\frac{w}{W}} \quad \ldots \quad \ldots \text{(XIII.)}$$

The weight of different kinds of concrete was given in Table XX., page 181; 8 to 1 Portland-cement concrete (well compressed) weighed 144 lbs. per cub. ft. with granite as the aggregate, 142 lbs. with ballast, 130 lbs. with Portland stone (and strong sand-stones will give about the same result), 131 lbs. with flints, and 129 lbs. with pottery.

For *walls with vertical face and with sloping or offset back*, the mean thickness may be *six-sevenths* of the thickness calculated by the formula.

For *walls with battered face and vertical back*, the mean thickness may be *six-sevenths* of T for a batter of 1 in 12, *four-fifths* of T for a batter of 1 in 8, and *three-fourths* of it for a batter of 1 in 6.

These calculations are all for walls to support ground level with the top of the wall. If the wall is carried higher than the ground, the added weight of the upper part will allow the lower to be made correspondingly thinner. If, however, the ground slopes up from the top of the wall, the additional thrust of this superincumbent material will require the wall to be correspondingly thicker. The methods of calculating the thickness of such "surcharged revetments" will be found in Rivington's "Notes," and in several other text-books, and need not be stated here.

An example, showing the use of formula XIII., may be advantageous to the student.

Find the thickness of a concrete wall 12 ft. high above the footings, required to support a bank of gravel and

sand, the concrete to be composed of Portland cement, sand and gravel. Then according to the Table, K = ·44, and w = 112 lbs., W = 142 lbs., and H = 12 ft.

Putting these figures for the letters in the formula, we get

(1) *with face and back vertical* (*Fig.* 54),

$$T = \cdot 44 \times 12 \times \sqrt{\frac{112}{142}} = 4 \cdot 68 \text{ ft.}$$

(2) *with vertical face, and sloping or offset back* (*Fig.* 55),

$$T = \frac{6}{7} \times 4 \cdot 68 \qquad = 4 \cdot 01 \text{ ft.}$$

(3) *with vertical back, and face battered* 1 *in* 8 (*Fig.* 56),

$$T = \frac{4}{5} \times 4 \cdot 68 \qquad = 3 \cdot 74 \text{ ft.}$$

These walls are shewn in section in Figs. 54, 55, and 56.

CRACKS.—To prevent cracks from expansion and contraction, in long retaining walls, a thin strip of wood or plate-iron 3 in. or 4 in. wide, is introduced edgeways into the face-concrete every 20 ft. or 30 ft., and is withdrawn before the concrete has properly set; this forms a kind of joint, which may be afterwards filled with mortar.

In the case of large concrete tanks (say, more than 15 ft. long) the walls should be protected as much as possible from changes of temperature by forming them underground or by filling around them with earth; under such circumstances no fear of cracks from contraction need be entertained. Concrete for tanks should contain sufficient sand and fine aggregate to render it homogeneous, and should be well rammed, but in addition to this it should be rather rich in cement and finished with a thin coat of cement-mortar or neat cement. Sometimes large underground reservoirs have been formed of concrete, with concrete piers at intervals supporting arched concrete ceilings. The whole structure can then be covered with earth, and by this means protected from great and sudden changes of temperature.

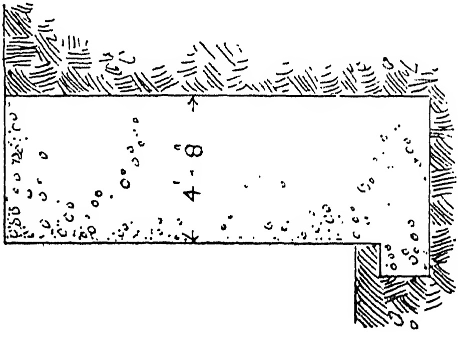


Fig. 54.—Retaining Wall with Face and Back vertical.

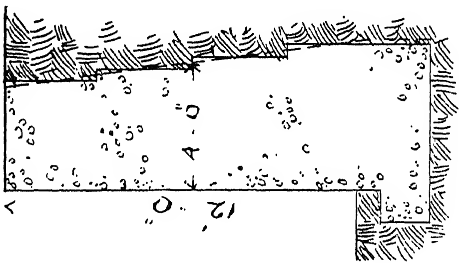


Fig. 55.—Retaining Wall with vertical Face, and sloping or offset Back.

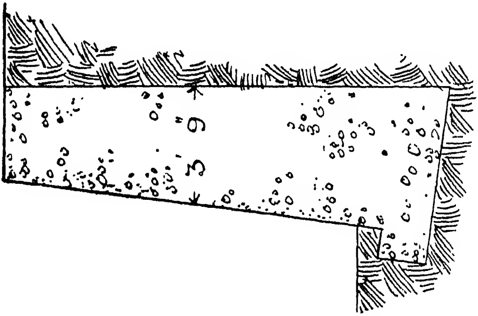


Fig. 56.—Retaining Wall with vertical Back and Face battered 1 in 8.

External Treatment.—If the concrete is well made with fine aggregate of a suitable nature, and if the shutters are smooth and true, a good finish can be obtained without any surface coating. Recessed joints may be formed as explained on page 312, and the faces of the blocks may be tooled, pitched, picked, or finished in other ways, exactly like ashlar.

1. *Facing-concrete.*—This was first used by Mr. T. Dyke, who, in 1869, began the extension of the breakwater at Hartlepool with common concrete hearting and superior facing. The latter consisted of one part Portland cement and four parts whinstone, broken in a Blake's crusher to $\frac{1}{2}$-in. gauge. The face of the wall was outlined with standards and shutters, and within these, at distances of 9 in. and 18 in. in the alternate layers, internal partition-boards were placed and kept in position by distance pieces extending from them to the shutters. The common concrete was deposited and rammed within the internal partition-boards, while immediately afterwards the face-concrete was deposited and rammed between the partition-boards and the shutters. The partition-boards were then withdrawn, and the two concretes were united by ramming along the line of junction. Each layer of concrete was 9 in. thick.

In 1874 Mr. Bernays adopted the same plan at Chatham, using a 1 to 12 concrete for the hearting or backing, and a 1 to 6 for the facing; the latter consisted of 1 part Portland cement, 2 parts sand, and 4 parts iron-furnace slag broken in a Blake's crusher to about $\frac{3}{4}$-in. cubes. The appearance of the walls is, says Mr. Bernays, far from unpleasing either in texture or colour, the surface being "invariably left with all imperfections, as it appears on the removal of the shuttering." Mr. Bernays has also used facing-concrete (without plastering) for the walls of water-tanks, pump-wells, &c., and for the exposed surfaces of coping, steps, curbs, paving, and building-blocks. The coping, which had a cross-section of 4 ft. × 2 ft., consisted of 1 part Portland cement and 8 parts gravel, faced

on the top and two sides with a 2-in. coat of cement and broken granite (1 to 2). The building-blocks, which measured 18 in. × 9 in. × 6 in., were composed of cement and gravel (1 to 10), faced 1 in. thick with cement and fine gravel (1 to 4). The surface of the coping, curbs, &c., is much improved by being dressed with a diamond-pointed hammer; "it is then difficult to distinguish the concrete from real granite."

In all cases of facing, the two kinds of concrete should be put in as nearly as possible simultaneously, in order that they may set into one mass.

2. *Rough-trowelling.*—Most frequently, the concrete walls of buildings are finished with some kind of stucco or rough-cast. Mr. Potter recommends for common work the system of "rough trowelling." When the concrete has thoroughly set, a stiff mortar of Portland cement and clean sharp sand (about 1 to 3) is applied with a plasterer's handfloat, and "is thoroughly worked into the crevices of the concrete, but leaving no body or coat on the surface." After being smoothed with water and a distemper-brush, the work is complete.

3. *Stucco.*—A proper coat of Portland cement and clean sharp sand (1 to 2 or 1 to 3) is most frequently employed for the external faces of concrete walls. The surface of this stucco can be finished in different ways; if a wood float, or a float covered with felt, be used, the sand is brought to the surface, and a rough texture is the result; if a steel float or trowel be used, an exceedingly smooth surface can be obtained; if after floating with the steel trowel the surface be finished by dabbing the trowel on it, a medium texture is obtained. The stucco can be ornamented by impressed designs, by raised stencilled patterns, by moulded cornices and architraves, and in other ways.

4. *Colour.*—Attempts have been made to give variety to stucco by mixing different colouring matters with the dry material, but in all such attempts there is a danger of the setting properties of the cement being injured, and the further disadvantage that the stucco may prove very

uneven in colour. Considerable variety could safely be given by the use of different coloured sands; but where these are not available other substances would have to be tried. Mr. Rowland Plumbe says that a dark red colour can be obtained by the use of purple-brown (oxide of iron), light red by Venetian red, blue by German ultramarine, and black by black manganese; the proportion he recommends is one cement, two sand, and one-tenth colouring matter.

Colour effect can also be obtained by means of good washable distemper such as the well-known "Duresco," or, of course, by painting, but the expense of continual colouring and painting would be a drawback to the use of concrete and stucco.

5. *Rough-cast.*—The good effect of a "rough-cast" of pink and grey granite chips on the bridges at Croft has already been mentioned. When rough-cast and "rough-trowelling" are adopted, the angles of the buildings and of all voids are sometimes finished with plain or moulded bands of cement a few inches wide, unless "artificial stone" or other dressings are employed.

6. *Sgraffito.*—Sgraffito work is another method of decorating a concrete wall. It was tried at South Kensington. A wall was covered with Portland cement coloured black, and on this a thin coat of Portland-cement stucco was laid, in which the design was scratched. After some years moisture got between the two coats, and the outer one peeled off. Sgraffito has, however, been successfully employed in other buildings, especially in small panels, pediments, &c.

7. *Half-timber work.*—The attachment of oak or other wood face-boards about 1 in. thick to the face of concrete walls, in imitation of half-timber work, has been advocated and tried. The panels thus formed can be finished with stucco or rough-cast. The face-boards can be attached to fixing-blocks inserted in the concrete as it is being deposited. This mode of decoration seems to be the outcome of a prize offered by *The Building News* some years ago for the best design for a concrete villa.

Of course, it will be said that this method of decoration is a sham; so, we may say, is much of the "half-timber work" used nowadays, for it is frequently merely a way of facing a brick wall. And, indeed, if we will be honest with ourselves, we must confess that shams exist largely in all our buildings, and, as a rule, the richer the building the greater the shams. But a great deal of rubbish has been spoken and written on this same subject of shams.

Sometimes the panels of proper half-timbered structures have been formed with concrete, temporary face-boards having been screwed to the framework to receive it. The sides of the framing should be grooved to afford a key for the concrete.

8. *Brick and Stone.*—Many concrete walls, especially dock-walls and other heavy engineering works, are faced with brick or stone bonding into the concrete; in the case of brickwork, it may be laid in groups of courses about 18 in. deep, the groups being alternately (say) 9 in. and 18 in. on bed. For the walls of buildings, a $4\frac{1}{2}$-in. brick facing has sometimes been used, tied to the concrete by means of hoop iron, or other metal ties.

A new kind of brick has just been invented for facing concrete walls, and for forming the soffits of arched concrete floors. The bricks are known as Shoppee's patent, and their peculiarity consists in having dove-tailed grooves at the back, which form a key for the concrete behind.

9. *Tiles, &c.*—The exterior of concrete walls may be covered wholly, or in parts for the sake of variety, with ordinary roofing tiles secured to laths, which may be nailed to fixing-blocks.

Some of the forms of artificial stone, such as modelled panels, balusters, finials, coping, &c., furnish a ready means of decorating concrete buildings. So also do tiles of various kinds, plain or ornamental, glazed or unglazed; modelled and moulded panels of terra-cotta can also be conveniently inserted. Prof. Aitchison mentions a palace in Berlin which is faced with unglazed paving tiles, and has window-dressings of majolica, and a frieze of glass-mosaic.

CHAPTER XXV.

CONCRETE BLOCKS, ARTIFICIAL STONE, &c.

In engineering works, concrete blocks of enormous size are sometimes used, and, employed in this way in the sea, they have several advantages over concrete deposited *in sitû.* But for buildings, concrete blocks must necessarily be small, and they are therefore very expensive when compared with monolithic concrete.

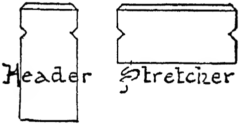


Fig. 57.—Concrete Blocks for Scarborough Sea-wall.

For facing the walls of promenades and sea-walls, concrete blocks of moderate size are often employed, as these have a better appearance than the plain surface of concrete as left by the shutters. The joints between the blocks also allow for expansion and contraction, and so prevent cracks from disfiguring the walls. Blocks have the further advantage that, as they are kept some time before being placed in position, any defective concrete is discovered during that time. Fig. 57 shows the concrete blocks used in the face of the Scarborough sea-wall.* The blocks measure about 24 in. × 12 in. × 12 in., and have triangular grooves in

* See Paper by Mr. Whateley Eliot in *Proceedings of the Inst. C. E.*, 1890-1, part iii.

their ends, and a chamfer $1\frac{1}{4}$ in. wide around the face of each; they were made of 1 part Portland cement, 2 parts sand, and 4 parts shingle, faced at the same time 2 in. thick with 1 part cement and 2 parts shingle, passed through a $\frac{1}{4}$-in. sieve and having all fine sand removed. They were kept one month before being placed in the wall, and were then set, in alternate courses of headers and stretchers, in Portland-cement mortar (1 to 2); the joints were well grouted, and in this way the blocks were dowelled together by means of the triangular grooves.

The river-wall adjoining the Thames at Fulham is of concrete, faced in part with concrete blocks. The wall is 9 ft. thick at the base, 18 in. at the coping, and about 20 ft. high. Above the river-bed it is faced with concrete blocks. The work was well described by its designer, Mr. J. P. Norrington, the Surveyor to the Vestry of Fulham, in a paper which was read by him to the members of the *Incorporated Association of Municipal and County Engineers*, and printed in *The Builder* for March 11, 1893. The accompanying figure is reproduced from *The Builder*. The concrete in mass was specified to consist of 1 part Portland cement (severely tested, and stored in bulk for 21 days), and 5 parts Thames ballast, mixed with *clean* water from a water-company's supply, as Thames water would not be allowed. The blocks were to have a facing 6 in. thick, composed of 1 part Portland cement and 3 parts Thames ballast passed through a $\frac{3}{8}$-in. sieve; the remaining portions of the blocks were to be of 1 cement and 5 ballast passed through a $1\frac{1}{2}$-in. sieve. They were to be cast in wood moulds of the shape shewn in the drawings, the parts of the moulds fashioning the faces and chamfered edges of the blocks to be "of planed and well-oiled American white wood." A dove-tailed-shaped groove was to be formed "on each side of each block," so that grout (1 cement and 1 sand) could be run in to form a dowel. In filling the moulds great care was to be taken that the two kinds of concrete did not "mix," while at the same time "the combination of the two layers into one block" was to be "perfect." The blocks were to

remain in the moulds for not less than 7 days, and were to be stacked (in such a manner that air could pass freely around them) for a further period of 21 days before being used.

The concrete mass forming the base of the wall was to be deposited in layers not more than 24 in. thick, and a V-shaped grip or groove 12 in. wide and 12 in.* deep was "to be left or formed in the middle, so as to form a key to the next layer."

The blocks were to be laid in courses, alternately 15 and 21 in. on bed, each being laid in cement mortar (1 to 3); the joints were not to exceed $\frac{1}{8}$ in. in thickness, and were to be pointed with neat cement. Each course of blocks was to be backed up with the mass concrete as soon as possible.

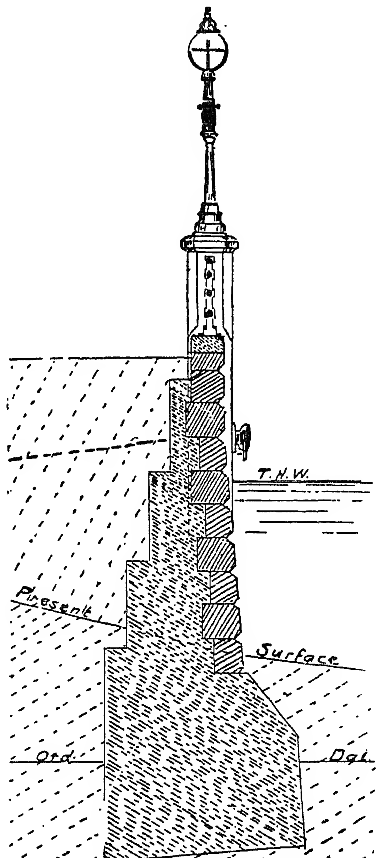


Fig. 58.—River-Wall at Fulham faced with Concrete Blocks.

"It was found," said Mr. Norrington, "that the faces of the blocks

* This is as printed in *The Builder*, but it is probable that it is an error, and that the depth should be 6 in.

when first made were full of small holes, owing to the air imprisoned in the process of filling the moulds, and they have all been rubbed with grit stone and trowelled over with a little fine sifted neat cement. Only sufficient cement has been used so as to fill up the holes, and no additional face has been put on the blocks."

These "pinholes" are frequently seen in concrete blocks of all kinds, but they are caused by using too much water in the concrete, a common fault,—and not by imprisonment of air, as Mr. Norrington suggests.

Concrete blocks have also been used in the form of voussoirs for large railway arches and the like. The Wallabrook Viaduct on the Plymouth, Devonport and South-West Junction Railway has seven arches, each 50 ft. span, built of concrete voussoirs; the concrete consisting of 1 part Portland cement, 1½ parts sand, and 4 parts broken stone. The Shillamill Viaduct on the same railway has twelve semi-circular arches of similar span and construction.*

Many patents have been taken out for concrete building-blocks of various kinds, Z-shaped, hollow, &c., but they are not often used, chiefly on account of their cost. Building by means of blocks is expensive for two reasons,—the blocks cannot be of large size, and they require skilled labour to lay them.

Concrete "dressings," however, are largely made, and can be used in combination with concrete deposited in mass. Steps, mullions, transomes, heads, sills, string-courses, panels, &c., moulded and enriched as required, can be obtained in various colours,—red, buff, brown, and grey. Concrete blocks of this kind are frequently known by the name of artificial stone, or by some special name. Some of the buff varieties look, at the first glance, like natural sandstone.

Artificial stone is true in line, and much of it is extremely durable. Inferior kinds often shew fine "hair-cracks," which are caused by the use of cement not sufficiently air-slacked, or by excess of cement in the surface-coat.

* *The Engineer*, May 30, 1890.

The variety of uses, to which concrete or artificial stone has been put, is surprising. There are Allen's concrete lintels, Edwards's concrete joists and studs, Brandon's "Stone-Felt" fire-proof doors, and other examples, all containing iron rods to give additional strength. There are also concrete sinks, drinking-troughs, ridge-tiles, and even telegraph poles, the last being tapering tubes, the walls of which are formed with wire netting embedded in concrete about an inch thick. In America and Germany hollow concrete blocks have been used for fire-resisting floors.

Indeed a quite bewildering number of patents for artificial stone have been taken out, but not many of them have been successful or profitable.

We may just mention the artificial stone of Messrs. W. H. Lascelles & Co., known as "Lascelles' Concrete," which has been used by many eminent architects, including Mr. Waterhouse, Mr. Christian, and Sir A. W. Blomfield. It is made in three colours,—red, buff, and grey,—and can be obtained in the form of balustrades, cornices, plinths, copings, sills, heads, columns, pilasters, finials, and indeed in nearly every form for which stone can be employed.

The Croft Granite, Brick and Concrete Co. also makes different kinds of architectural features and dressings, in various colours. Among other things, they manufacture small coloured tiles with impressed patterns, suitable for wall decoration. One kind of tile is really of considerable artistic merit; it is made of Portland cement and the finest *dust* formed in crushing their syenite. These, together with a small quantity of colouring matter, are mixed and thoroughly pressed into a polished metal mould which has a very slightly impressed floral design.

The resultant tiles, which are about 12 or 15 in. square, ring almost like pottery when struck, and have a smooth shining surface with the floral design in the lowest possible relief. They can be used for the panels of dadoes, chimney-pieces, &c.

The same company makes concrete posts about 9 in. square, to fit into concrete sockets which are embedded in

the ground; holes are left through the posts to receive wrought iron pipes. These make a firm and durable fence. The posts cannot rot like wooden ones, and do not require painting.

Messrs. F. Rosher & Co. issue a large catalogue containing many excellent examples of their artificial stonework, in the form of balusters and other architectural features, fountains, statues, vases, &c.

Messrs. Fambrini & Daniel, of Lincol , make an "imperishable red concrete," and mould it into a large variety of architectural features, such as cornices, strings, modelled panels.

The manufacture of artificial stone, however, although it is invariably a kind of concrete, and most frequently a Portland-cement concrete, is beyond the scope of this work.

Fire-resisting Partitions.—Concrete blocks are frequently used in the construction of fire-resisting partitions. Plaster of Paris is more commonly adopted than Portland cement, as it is cheaper and lighter. A light aggregate is also selected, such as coke-breeze, and in some cases saw-dust is added or small fragments of cork. Many of these partition-blocks have been patented, the principal difference being in the method of jointing. In the "Mack" partitions, the blocks are 6 ft. long and 12 in. high, and range in thickness from 2 to 4 inches. Semi-circular grooves are formed in the edges of the slabs along the two ends and one side, and a convex tongue along the other side. The horizontal joints may therefore be described as tongued and grooved; the vertical joints are grouted with plaster, which fills the circular hole formed by the two adjacent grooves. In some of the Mack slabs, reeds are embedded horizontally to reduce the weight, and to render the partitions more sound-resisting. In some kinds of slab, holes are formed at intervals throughout the entire length.

In H. Gust & Co.'s "Fireking" partition, which has recently been tested with satisfactory results by the British Fire Prevention Committee, the slabs are of plaster of Paris and coke-breeze in equal proportions, and the surfaces

are grooved to afford a key for a thin finishing coat of plaster. The edges are grooved and corrugated, and form an excellent joint when run with plaster; but the principal feature of this partition is the reinforcement of iron wires. In the case of a partition between two brick walls, holdfasts are driven or built into the brickwork, and horizontal wires are attached to these at the levels of the bed joints of the slabs; short vertical wires are attached to the horizontal wires at the end joints, the slabs being laid "to break joint." The wires are laid in the grooved edges of the slabs, and are entirely embedded in the plaster used in making the joints. For attaching the horizontal wires to iron or steel columns and stanchions, the metal is tapped and a screwed eye inserted. Special arrangements are adopted for angles, openings, &c. An important advantage of this method of construction is that the weight of the partition is almost wholly supported by the walls to which it is connected.

Monolithic concrete partitions are built between wooden shuttering in the manner described for walls. Partitions of this kind, reinforced with horizontal and vertical wires, are sometimes only 2 in. thick.

CHAPTER XXVI.

ARMOURED OR REINFORCED CONCRETE.

1. Introductory.

In previous chapters mention has been made of some of the methods adopted for increasing the strength of concrete structures by means of iron or steel rods, bars, or meshwork, but it may be useful to give, in a separate chapter, a fuller account of this important subject. Various names have been suggested for this type of construction, the most important being "Armoured Concrete" and "Reinforced Concrete"; neither is entirely satisfactory, but the latter is, perhaps, the better of the two. "Ferro-concrete" is a more descriptive name, which is sometimes used. The terms are restricted to combinations of concrete, and iron or steel, in which the metal is used in small sections disposed in such a manner as to give the greatest increase of strength with the smallest amount of material. We have seen that concrete offers a much smaller resistance to tension than to compression, and as a rule, the iron is inserted in that part of the concrete which will be subjected to a tensile stress, the part in compression being left without any reinforcement. Occasionally, however — as in columns and walls—the resistance of the concrete under compression is also increased by inserted metal. When this method of construction was introduced, fears were expressed that such dissimilar materials as concrete and iron would not work in harness together, but it has now been demonstrated that the fears were greater than the case warranted. The practical application of the theory of reinforcement during the last ten or twenty years, both in Europe and

America, has clearly shown that the two materials can with safety and economy be used in conjunction, and that each will bear its proper share of the load, if due precautions are taken. Reinforced concrete is not only stronger than concrete alone, but has a greater deflection before rupture, and therefore does not fail under heavy loads without warning ; it is also less liable to collapse in case of fire.

2. Beams, Floors and Roofs.

Stresses and Reinforcement.—In a beam *supported* at the ends, the lower portion is in tension and the upper in compression. The tension reinforcement will therefore be required near the soffit. The thickness of the concrete below the reinforcement will be largely governed by the degree of fire resistance desired.

In a beam *fixed* at one end only (*i.e.*, a cantilever), the upper part is in tension, and the tension reinforcement must be near the upper surface.

In a beam *fixed* at both ends, the lower portion is in tension in the central part of the span, and the upper in tension near the supports. If such a beam is uniformly loaded, the points of change from lower to upper tension (known as the points of contra-flexure) will be at a distance of $\frac{1}{4}$ of the span from each support. The position of the points will, however, vary with unequal loading. In beams of this kind, it is customary to continue the lower tension-rods to the points of support, and to insert upper tension-rods from each support to a distance of about three inches beyond the nearest point of contra-flexure.

In beams *continuous* over one or more points of support, a similar variation of the stresses occurs, the points of contra-flexure varying with the number of the supports and the distribution of the load. It is therefore necessary to insert upper tension-rods extending over the supports to (or rather beyond) the points of contra-flexure, in addition to the lower tension-rods, which take up the tension in the central portions of the spans.

Short rods are sometimes inserted at the points of support to give additional resistance to the shearing stresses.

Floors are generally regarded as beams fixed or supported at the two ends, no allowance being made for any increase of strength due to the supporting of the two sides. This method of calculation is adopted because the reinforcement is not, as a rule, equally strong in both directions, and also because the increase of strength due to the fixing or supporting of the sides still requires elucidation; in square slabs, the increase of strength will be considerable, if the reinforcement is equally strong in both directions, but the more the width is increased in proportion to the span, the less will the increase be. It is safer to regard floors as beams, and to insert the tension-rods in the positions indicated above.

Stuart's Armoured Concrete.—In the Monier system, which was one of the earliest, round iron rods are used, but before Monier's invention was known in this country, a similar method of reinforcement had, it is said, been adopted by Stuart's Granolithic Stone Co. Many of the floors constructed by this firm have been a source of wonder to architects and others, who were under the impression that the floors consisted of concrete only; the fact is that they were reinforced with iron rods. Numerous tests have been made of reinforced Granolithic, but the most instructive are those carried out (on behalf of Sir Benjamin Baker and his partner, Mr. Basil Mott) for the London Central Railway Co. Eight beams were tested in 1903–4, namely, six with round rods, one with expanded metal, and one with barbed wire. The last proved to be a failure. The tests with round rods are given in Table XXXI., Nos. 1 to 6; Nos. 1 to 4 consisted of one part of cement to three parts of crushed granite (by measure), reinforced with six $\frac{3}{8}$-in. round tension-rods of the same length as the beams, and with similar rods 1 ft. 6 in. long laid transversely and wired to the longitudinal rods with No. 22 gauge wire; in No. 5 four parts of crushed granite were mixed with one

part of cement, and nine $\frac{1}{4}$-in. rods 7 ft. 6 in. long and eight 5 ft. 6 in. long were used; No. 6 was similar in every respect, except that carefully-prepared Thames ballast was used instead of crushed granite. No. 7 is the record of a reinforced Granolithic beam tested in 1904 by David Kirkaldy and Sons; it was composed of cement and crushed granite (1 to 3), and was reinforced with three $\frac{3}{8}$-in. round rods in the upper or compression side and six $\frac{5}{8}$-in. square rods in the lower or tension side, the latter being in two planes, four near the soffit and two above. In order that the figures may be more conveniently compared with those in preceding tables, I have converted the breaking loads into cwts.; I am also responsible for all the figures in columns 4, 10, 11 and 13.

The co-efficients or constants in column 13 of Table XXXI. may be compared with those for simple concrete beams, given in Table XXII., pp. 190—191, but the enormous increase of strength due to the reinforcement will be more correctly appreciated by comparison with the following record of tests of Granolithic beams in which iron was not introduced. Six Granolithic paving slabs were tested by Kirkaldy in 1902; the clear span was 24 in., mean breadth 23·85 in., mean depth 2·1 in., and mean central breaking load 2,173 lb. Allowing for the weight of the material, we obtain 3·66 as the mean value of C, which is less than one-eighth of the lowest value for the reinforced concrete.

It will be useful to ascertain if the breaking weights recorded in Table XXXI. coincide with the results obtained by theoretical calculations on the lines indicated in Chapter XVII. The tensile strength of the concrete will not be taken into consideration. The crushing strength of Granolithic has been tested by Kirkaldy at various times. The mean of six tests of 2-in. cubes was 217 tons per sq. ft. We will assume that the crushing resistance of good Granolithic at the age of the beams tested is 200 tons per sq. ft., or (say) 3,000 lb. per sq. in. This is the maximum stress on the upper side of the beam; the mean stress will be one-half, namely, 1,500 lb.

TABLE XXXI.

TRANSVERSE STRENGTH OF STUART'S REINFORCED GRANOLITHIC BEAMS, SUPPORTED AT THE ENDS.

1	2	3	4	5	6	7	8	9	10	11	12	13
No.	Composition of Concrete, 1 p.c. to	Longitudinal Reinforcement.	Ratio of Sectional Areas of Iron and Beam.	Clear Span.	Breadth.	Depth.	Age when Tested.	Distributed Breaking Load.	Approx. Weight of Beam.	Total Load.	Maximum Deflection at Centre.	Value of C. $W = \frac{4}{3} C \frac{BD^2}{L}$.
				In.	In.	In.	Days.	Cwt.	Cwt.	Cwt.	In.	
1	3 granite	Six $\frac{3}{8}$-in. round tension-rods 7 ft. 6 in. long	1 : 72	84	19	2·5	24	56	3	59	$1\frac{7}{16}$	31·3
2	,,	,, ,,	1 : 57	,,	,,	2·0	,,	36·2	2·4	38·6	$1\frac{1}{2}$	31·9
3	,,	,, ,,	1 : 72	,,	,,	2·5	50	57·2	3	60·2	$1\frac{1}{4}$	31·9
4	,,	,, ,,	1 : 57	,,	,,	2·0	,,	44·6	2·4	47	$1\frac{9}{16}$	38·9
5	4 granite	Nine $\frac{1}{4}$-in. round tension-rods, 7 ft. 6 in. long, and eight $\frac{1}{4}$-in. do. 5 ft. 6 in. long	1 : 57	,,	,,	2·5	35	64	3	67	$1\frac{11}{16}$	35·5
6	4 Thames ballast	,, ,,	1 : 57	,,	,,	,,	,,	76·4	3	79·4	$1\frac{1}{4}$	42·1
7	3 granite	Three $\frac{3}{8}$-in. round rods at compression side and six $\frac{5}{8}$-in. square rods at tension side	1 : 67	120	12	15	333	736*	16	752	$\frac{1}{2}$†	50·1

* This beam was tested with a central load, the breaking load being 368 cwt.

† This deflection was observed when the load was 40,000 lb., or about 97 per cent. of the breaking load.

per sq. in. The tensile resistance of the steel rods is about 30 tons, or 67,200 lb. per sq. in., and as the rods are of small diameter and in one plane, the full resistance is available. In the tests numbered 1 to 4, the total sectional area of the six longitudinal rods is $\frac{2}{3}$ sq. in. If the neutral axis is assumed to pass through the centre of the beam, the area under compression will be (for beams 1 and 3) 19 in. $\times$ $1\frac{1}{4}$ in. $=$ $23\frac{3}{4}$ sq. in., and the available resistance to compression will be $23\frac{3}{4}$ sq. in. $\times$ 1,500 lb. $=$ 35,625 lb. The ultimate resistance of the tension-rods will be $\frac{2}{3}$ sq. in. $\times$ 67,200 lb. $=$ 44,800 lb. As these resistances are unequal, it is probable that the position of the neutral axis does not accord with the assumption.

To find the position of the neutral axis, we will assume that the centre line of the tension-rods is at one-sixth of the depth measured from the soffit upwards, $=$ ·416 in. Let $=$ the distance of the neutral axis from the upper surface of the beam; then, the breadth of the beam being 19 in., (compression) 19 x $\times$ 1500 lb. $=$ (tension) 44,800 lb. and $x = \dfrac{44{,}800}{19 \times 1500} = 1{\cdot}572$ in.

The centre of pressure in the compression area is $\frac{2}{3}$ of 1·572 in. $=$ 1·048 in., above the neutral axis, and the centre of the rods is $2{\cdot}5 - 1{\cdot}572 - {\cdot}416 = {\cdot}512$ in. below the neutral axis. The arm of the couple is $1{\cdot}048 + {\cdot}512 = 1{\cdot}56$ in., and the moment of resistance is the product of this and one of the resistances, thus, *compression*, $19 \times 1{\cdot}572 \times 1500 \times 1{\cdot}56 = 69{,}891$ inch-lb., or *tension*, $\frac{2}{3} \times 67{,}200 \times 1{\cdot}56 = 69{,}888$ inch-lb.

The bending moment of a beam uniformly loaded, and supported at the ends is $\dfrac{W\,L}{8}$, and as the bending moment equals the moment of resistance, we obtain the following equation, L being 84 in., $\dfrac{W \times 84}{8} = 69{,}888$, and

$$W = \frac{69{,}888 \times 8}{84} = 6{,}656 \text{ lb.} = 59{\cdot}4 \text{ cwt.}$$

This is almost exactly the same as the actual breaking weights recorded in column 11 of the Table, namely, 59 cwt. for beam No. 1, and 60·2 for No. 3.

In the case of beams 2 and 4, which are only 2 in. thick, the neutral axis, if the same method of calculation is adopted, will fall within the thickness of the rods. As the rods are inserted merely for resisting tension, the beams are not correctly proportioned, unless we have over-estimated the tensile resistance of the steel or under-estimated the compressive resistance of the concrete. Assuming that the neutral axis touches the upper side of the rods, we find that the breaking weight will be 39·1 cwt., if calculated from the resistance of the concrete, and 42·5 cwt., if calculated from the resistance of the rods. In a theoretical investigation, the smaller of these would be assumed to be correct. It accords very closely with the actual breaking weight of beam No. 2. The theoretical breaking weight of 42·5 cwt., the larger of the two mentioned above, would be obtained from the concrete, if its resistance to compression were 12 per cent. more than the 1,500 lb. per sq. in. allowed in the calculations. This is a very small difference in the case of such a variable material as concrete. But even if this additional resistance is admitted, the theoretical breaking weight of 42·5 cwt. is about 10 per cent. less than the actual breaking weight of beam No. 4, which certainly gave exceptionally good results.

Beams 5 and 6 were prepared and tested for the purpose of comparing the strength of granite and Thames ballast, the result being in favour of the latter. The ballast was carefully washed, the excess of sand being eliminated, and the flints being broken and screened through a $\frac{3}{4}$-in. mesh sieve.

Test No. 7 shows that reinforced concrete is adapted for use in the form of lintels and girders. The reinforced beam, 12 in. broad, 15 in. deep, and with a clear span of 10 feet, broke under a load of about 37 tons, and is therefore equal in strength to a rolled steel joist 9 in. $\times$ 4 in. $\times$ 21 lb. per foot.

Reinforced concrete beams are now employed in the construction of floors. A floor of this kind was made by Stuart's Granolithic Stone Co., and tested by W. H. Thomas, M.Inst.C.E. The slab measured 19 ft. 2 in. × 13 ft. 1 in. × 3 in., and was supported on all sides with clear spans of 18 ft. 6 in. longitudinally, and 12 ft. 2 in. transversely. Under the centre of the slab, transversely, a reinforced concrete beam was formed, 9 in. broad, and $13\frac{13}{16}$ in. deep below the slab. The floor was first loaded on May 18th, 1894; on June 28th, under a distributed load of 15 tons, the deflection at the centre of each bay was $\frac{3}{16}$ in.; on July 4th, load 20 tons, deflection $\frac{5}{16}$ in.; on July 9th, load 37 tons, deflection $\frac{3}{8}$ in.; on October 9th the load was increased to 64 tons. The weight of the slab and binder was "about 5 tons," so that the total distributed load was 69 tons, or 6·1 cwt. per sq. ft., and this load was carried without failure. The details of the reinforcement are not stated.

The "Ransome" Floors.—In the United States of America this type of construction has been largely adopted, but before considering what may be termed "coffered" floors, it will be well to continue the subject of flat slabs. In 1884 Ernest L. Ransome patented his system of reinforcing concrete with twisted iron. The advantages claimed for twisted iron are that it cannot be drawn through the concrete, and that the cold twisting increases the tensile strength of the iron to a considerable degree. Experiments have shown that the strength of $\frac{3}{4}$-in. square commercial iron is increased about 17 per cent. with two twists per lin. foot, and about 25 per cent. with six twists per foot. The figures adopted by the Ransome and Smith Co. in their calculations are 20,000 lb. per sq. in. for the safe load on twisted iron in tension, and 500 lb. per sq. in. for the safe maximum load on concrete in compresson. It is stated that "the margin of safety in the use of concrete has been made unnecessarily large; it was thought best to err on this side rather than the other, in order to meet the varied quality of materials used throughout the United States." Table XXXII. has

been compiled from the tables issued by the company. I have checked some of the figures in the manner already described, and have found them correct. The "depth" in column 5 is the distance from the top of the concrete to

TABLE XXXII.

FLAT CONCRETE FLOORS REINFORCED WITH RANSOME'S TWISTED IRON.

Safe Load per sq. ft.	Approx. Weight of Floor per sq. ft.	Size of Square Twisted Iron Rods.	Distance between Rods.	"Depth"	Thickness.	Approx. Cement per 100 sq. ft.	Approx. Aggregate per 100 sq. ft.	Approx. Iron per 100 sq. ft.	
Lb.	Lb.	In.	In.	In.	In.	Lb.	C. yds.	Lb	
50	30	¼	6	2	2½	600	·90	53	6 ft. span.
75	36	¼	5	2½	3	720	1·08	63	
125	42	¼	4½	3	3½	840	1·26	69	
250	54	½	10	3¾	4½	1,080	1·62	139	
500	75	½	9½	5½	6¼	1,500	2·25	145	
50	48	¼	3	3½	4	960	1·44	100	9 ft. span.
75	48	¼	3	3½	4	960	1·44	100	
125	63	½	9	4½	5¼	1,260	1·89	132	
250	81	½	8	6	6¾	1,620	2·43	167	
500	103	½	6	8	8¾	2,060	3·09	213	
50	60	¼	2½	4½	5	1,200	1·80	119	12 ft. span.
75	66	¼	2	5	5½	1,320	1·98	147	
125	81	½	7	6	6¾	1,620	2·43	165	
250	105	½	5	8	8¾	2,100	3·15	250	
500	141	¾	9	11	11¾	2,820	4·23	306	
50	81	½	7	6	6¾	1,620	2·43	165	15 ft. span.
75	87	½	6	6½	7¼	1,740	2·61	192	
125	105	½	5½	8	8¾	2,100	3·15	210	
250	138	¾	9½	10½	11½	2,760	4·4	291	
50	99	½	5½	7½	8¼	1.980	2·97	210	18 ft. span.
75	111	½	5	8½	9¼	2,220	3·33	230	
125	138	¾	9½	10½	11½	2,760	4·14	270	
250	168	¾	7	13	14	3,360	5·04	386	

the centre-line of the tension-rods; the "thickness" in column 6 is the total depth or thickness of the floor. The calculations appear to have been based on the assumption that the neutral axis passes through the centre of the "depth," and the tensile resistance of the concrete below the neutral axis has been neglected; the slabs are calculated as beams, supported at the ends only. The safe loads in column 1 are the loads which the floors will safely bear in excess of their own weight. The concrete should be composed of cement and aggregate in the proportion of 1 to 3, if the cement "will develop a tensile strength of 350 lb. per sq. in. in 14 days; if a weaker cement is used, the quantity should be proportionately increased." The aggregates, which are recommended, are the following ("about in the order of merit"): Hard limestone, hard clinker brick, hard broken pottery, granite or basalt, hard clinkers, broken flint or other hard rock, and gravel. Dirty or soft clayey rock should be avoided. "The aggregates should be broken so as to pass through an inch ring, and the fine dust removed by washing or screening (washing preferred); in mixing add sufficient water to bring the mass into a soft pasty condition, and tamp it thoroughly into place." In addition to the tension-rods extending in the direction of the span, auxiliary rods are laid at right angles (*i.e.*, parallel to the supported ends), at distances of about 3 ft., these rods being $\frac{1}{4}$ in. square for loads up to 125 lb. per sq. ft., and $\frac{1}{2}$ in. square for heavier loads.

The Ransome coffered or panelled floors (Fig. 59) are an interesting development, and are considerably stronger than flat floors containing the same amount of material. Table XXXIII. has been compiled from the tables issued by the Ransome and Smith Co. The calculations can be made in the manner already described, the concrete web being neglected. The tension-rods are 2 ft. 6 in. from centre to centre, and it is most convenient to consider the floor as a series of beams, each containing one tension-rod. Let us take for an example the floor 12 ft. span, carrying a safe load of 125 lb. per sq. ft. The thickness of the upper slab

TABLE XXXIII.

Panelled Concrete Floors Reinforced with Ransome's Twisted Iron.

Safe Load for Floor per sq. ft., in lbs.	Approx. Weight of Floor per sq. ft., in lbs.	Size of Twisted Iron Bars, in inches square.	"Thickness," in inches.	Depth of Concrete, in inches.	Approx. Cement per 100 sq. ft., in lbs.	Approx. Aggregate per 100 sq. ft., in yards.	Approx. Iron per 100 sq. ft., in lbs.	
50	19	½	1	8	380	·57	37	
75	23	¾	1·5	5	460	·69	84	
125	33	¾	2	8·5	660	·99	84	12 ft. span.
250	43	1	2·5	9	860	1.29	148	
500	59	1	3	17	1,180	1·65	148	
50	20	¾	1	6	400	·60	84	
75	28	¾	1·5	9	560	·84	84	
125	34	1	2	8	680	1·02	148	15 ft. span.
250	52	1	2·5	15	1,040	1·56	148	
500	65	1¼	3	17·5	1,300	1·95	232	
50	23	¾	1	9	460	·69	84	
75	32	¾	1·5	13	640	·96	84	
125	40	1	2	11	800	1·20	148	18 ft. span.
250	53	1¼	2·5	13	1,060	1·59	232	
500	67	1½	3	17	1,340	2·00	333	
50	28	¾	1	13·5	560	·84	84	
75	34	1	1·5	11	680	1·02	148	
125	46	1	2	16	920	1·38	148	21 ft. span.
250	62	1¼	2·5	19	1,240	1·86	232	
500	87	1¾	4	18	1,740	2·61	454	
50	36	1	1·5	11·5	720	1·08	148	
75	42	1	1·5	16	840	1·26	148	
125	50	1¼	2	15	1,000	1·50	232	25 ft. span.
250	70	1½	3	18·5	1,400	2·10	333	
500	115	2	5·5	21	2,300	3·45	593	
50	44	1	1·5	18	880	1·32	148	
75	52	1	1·5	23·5	1,040	1·56	148	
125	64	1¼	2	23·5	1,280	1·92	232	30 ft. span.
250	90	1½	3	29	1,800	2·70	333	
500	140	2	5·5	31	2,800	4·20	593	
50	58	1	1·5	38	1,160	1·74	148	
75	77	1¼	2	31	1,540	2·31	232	40 ft. span.
125	101	1½	3	34	2,020	3·03	333	

is 2 in., as stated in the table, and the breadth from centre to centre of the panels is 2 ft. 6 in. The tension-rod is $\frac{3}{4}$ in. square, and the "depth" from the top of the slab to the centre of the rod is 8·5 in. The sectional area of the slab is therefore 30 in. × 2 in., but the resistance to compression would probably be over-estimated if the whole of this were assumed to form part of the beam; as a rule, therefore, the breadth of the beam is assumed to be as shown by the shaded portion of Fig. 60, one-third of the breadth of the slab on each side of the central line being omitted. In

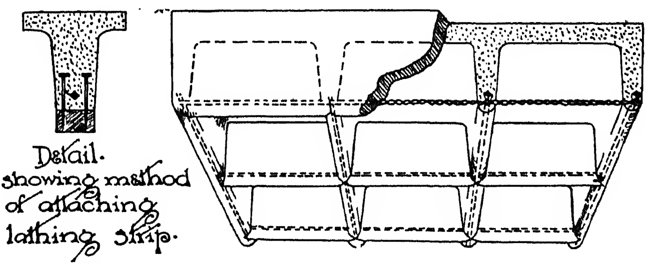


FIG. 59.—Panelled Floors reinforced with Ransome's Twisted Iron.

this case the breadth is 21 in. We therefore obtain the following safe resistances:

Compression, $21 \text{ in.} \times 2 \text{ in.} \times \frac{500 \text{ lb.}}{2} = 10{,}500 \text{ lb.}$

Tension, $\frac{3}{4} \times \frac{3}{4} \times 20{,}000 \text{ lb.} = 11{,}250 \text{ lb.}$

The centre of pressure in the slab is at a distance of one-third of its thickness from the top, namely, $\frac{2}{3}$ in., and the arm of the couple is therefore $7\frac{5}{6}$ in. Take the smaller of the two resistances, and we obtain the following equation:—

$$\frac{W\,L}{8} = 10{,}500 \times 7\tfrac{5}{6} = 82{,}250,$$

$$W = \frac{82{,}250 \times 8}{144} = 4{,}569 \text{ lb.}$$

This is the total safe load, and must be divided by the area of the floor supported by the beam to obtain the load per sq. ft.—

$$\frac{4,569}{12 \times 2 \cdot 5} = 159 \text{ lb. per sq. ft.}$$

Deduct from this the dead weight of the floor as stated in the table, namely, 33 lb. per sq. ft., and the safe load which can be placed on the floor is shown to be 119 lb. If the calculation is based on the resistance of the iron, the safe load works out to 130 lb. per sq. ft.

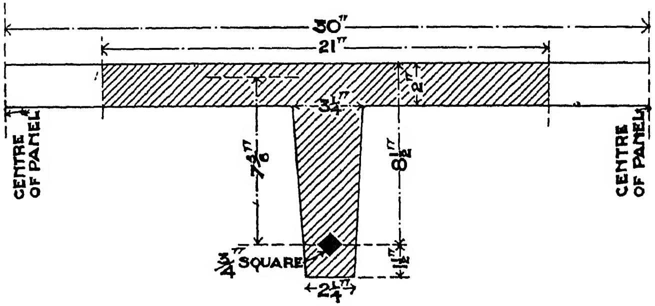


Fig. 60.—Detail of Ransome's Panelled Floor.

The following proportions are observed for the web; the distance from the centre of the bar to the soffit of the web is twice the thickness of the bar, the width at the bottom is three times the thickness of the bar, and the width at the top is 1 in. more. The concrete is 1 to 3, as described for the flat floors. Special moulds are of course required for forming these floors, and the first portion of the concrete is deposited in the web up to the level of the tension bar, which is then laid and tamped down into the concrete, and the remaining concrete is immediately deposited. Transverse webs reinforced with smaller twisted rods ($\frac{1}{4}$ in. square for floors where the main rods do not

exceed $1\frac{1}{4}$ in. square, and $\frac{1}{2}$ in. square for stronger main rods) are formed at distances ranging from $2\frac{1}{2}$ ft. to 5 ft. The twisted rods in the webs of panelled floors are generally secured by means of a number of $\frac{1}{8}$-in. rods, each of which is loosely bent in a spiral form around the tension-bar, and turned up at the ends to within $\frac{1}{2}$ in. of the surface of the floor; the ends of each rod are about a foot apart, and an interval of one foot occurs between the successive rods throughout the length of the tension-bar. Sometimes the coffers are exposed to view, the webs being plain or moulded in a simple manner. Flat ceilings may also be formed under the floors; in one method, shown in detail in Fig. 59, wood plates are laid on the centring under the webs, and the concrete is deposited around the coach-screws fixed in the upper surface of the plates. To these plates the wood or metal lathing is attached. Details of floors of this kind up to 60-ft. span are given in the Ransome publications.

The New Expanded Metal Company's Floors.—In this system, as in those already described, the tensile strength of the concrete is reinforced by metal, but the metal is in the form of a network, which is made by cutting slits in a sheet of steel and expanding it laterally. The meshes commonly used in floors are 3 in. wide and 8 in. long, but the strands of metal range from $\frac{3}{16}$ in. $\times$ $\frac{3}{32}$ in. to $\frac{1}{2}$ in. $\times$ $\frac{1}{4}$ in. or more, according to the span and load. The longer axis of the mesh is laid in the direction of the span, *i.e.*, from support to support, and the metal should overlap the supports where possible. The side joints in the sheets should also be overlapped 3 in. The expanded metal is placed on the temporary centring, and lightly nailed to it where necessary. It is recommended by the company that the concrete should be composed of *one* part of the best Portland cement to *four* parts of "clinker, brick, slag, stone, granite, &c., broken to pass a $\frac{3}{4}$-in. mesh sieve, and having about 30 per cent. of fine stuff in its measure," the materials to be turned three times dry, and three times after water has been added. If the

concrete is "thoroughly well scraped, spaded and tamped down into the meshes," it is said that the expanded metal will be lifted "into its ideal position, namely, about $\frac{1}{2}$ in. from the [lower] face of the concrete." The temporary centring may be "lime-whited, washed with soap water, or covered with oiled paper, to prevent the concrete adhering to it; the oiled paper gives the best results, and can be easily stripped off after the centring has been struck."

The expanded metal is of such a form that it cannot possibly be drawn through the concrete, and the labour of laying it is very little. That the metal greatly increases the strength of the flooring has been clearly proved. In 1896 beams 24 in. wide and 3 in. deep were tested by Messrs. Fowler and Baker. The concrete in all cases was composed of *one* part Portland cement, *one* part sand, and *two* parts Thames ballast passed through $\frac{3}{4}$-in. meshes, and with all the sand screened out. In one series, the spans were 78 in., and in the other 42 in. The tests were not very exact, as the loads consisted of rails weighing 6 cwt. each. The breaking weights give the following values of C for use in the Formula II., p. 193:—*Beams without expanded metal*, 2·7, 2·7, 2·94, 2·94; *Beams with expanded metal*, (1) strands $\frac{7}{32}$ in. × $\frac{3}{32}$ in., 17·33, 17·33, 12·57, 20·44; (2) strands $\frac{7}{32}$ in. × $\frac{5}{32}$ in., 18·95, 18·95, 17·82, 22·19. There was "no appreciable deflection" in the concrete beams, but the reinforced beams deflected from $\frac{9}{32}$ in. to $1\frac{3}{16}$ in. before rupture. The age of the beams ranged from 63 to 77 days. For the smaller strands the ratio of metal to concrete was as 1:219, and for the larger as 1:131. Two tests were made by Mr. James Mansergh, the concrete being composed of *one* part cement and *four* parts broken rock ($\frac{3}{4}$-in. gauge) and sand: span 81 in., breadth 48 in., depth 6 in.; age when tested 88 days; value of C for concrete 4·54, and for reinforced concrete ($\frac{1}{4}$ in. × $\frac{3}{16}$ in. strands) 18·64. The deflection of the concrete beam was "not observed"; that of the reinforced beam was $\frac{1}{2}$ in. Other tests, made by a committee of the Northern Architectural Association, gave more curious

results. All the beams were 42 in. wide, but those consisting of concrete only were 8 in. deep, and the reinforced beams 5 in. deep; the spans were 96 in., 78 in. and 60 in., one beam of each kind being tested for each span. The values of C for the concrete beams were 0·88, 0·91 and 2·33, and for the reinforced beams (strands $\frac{1}{4}$ in. $\times$ $\frac{3}{16}$ in.) 17·34, 19·63,* and 12·00.* The concrete was somewhat weak, having only *one* part of cement to *five* parts of "ordinary Tyne ballast." Other tests were made with thinner beams of 1 to 3 concrete, and gave the following results: for concrete only, 2·03 and 1·85; for reinforced concrete (strands $\frac{1}{4}$ in. $\times$ $\frac{1}{8}$ in.) 26·13 and 18·68. In the last series the ratio of metal to concrete was as 1 : 144, and in the first as 1 : 160. All the beams were nearly four months old when tested.

In calculating the strength of floors containing expanded metal, it is necessary to bear in mind that there are two strands of metal for each 3-in. mesh, making eight strands in each foot of breadth. It has been said that, as the strands run diagonally and not directly from support to support, they are subject to considerable shearing stress, which reduces their tensile resistance one-half, but this view does not appear to be borne out by the tests.

In the company's catalogue it is said that the sectional area of the steel should be $\frac{1}{2}$ per cent. of that of the concrete, the No. 9 sheets with $\frac{3}{16}$ in. $\times$ $\frac{1}{8}$ in. strands being recommended for 3-in. concrete, No. 8 with $\frac{1}{4}$ in. $\times$ $\frac{1}{8}$ in. strands for 4-in., and No. 30 with $\frac{3}{8}$ in. $\times$ $\frac{3}{16}$ in. strands for 9-in. Theoretical investigations and actual tests show that the sectional area of the metal is too little to balance the resistance of the concrete, and better results would be obtained by using a greater percentage of metal.

A slab of concrete 16 ft. square and 7 in. thick, supported on all sides to give a clear span of 15 ft. in each direction, and reinforced with one layer of No. 10 sheeting

* These are calculated from the maximum loads applied, which did not rupture the beams ; the true values of C are, therefore, higher than those stated.

having 3-in. meshes and $\frac{1}{4}$ in. × $\frac{3}{16}$ in. strands, was tested at Glasgow in 1903 by Messrs. A. T. Walmisley, J. P. Allen, and A. H. Morton, and failed under a distributed load of 56 tons 11 cwt. The fact that the fractures radiated "from the centre to the angles of the square" seems to show that the supporting of all the

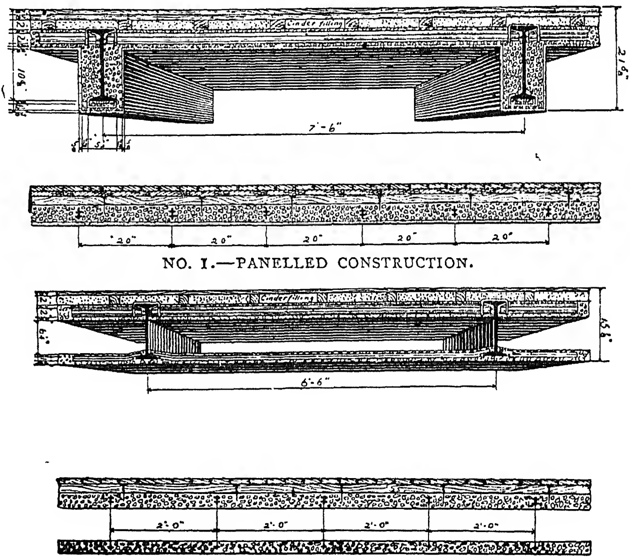


FIG. 61.—The Columbian Systems of Fire-resisting Flooring—Longitudinal and Transverse Sections.

sides increased the strength, but the test would have been more useful if a *beam* of similar design and materials had also been loaded to rupture.

Tests of two beams (mentioned above) containing the same reinforcement, and of nearly the same thickness but of inferior concrete, yielded a constant of 18, and from this the breaking weight of a beam of the same dimensions

as the unsupported portion of the slab (namely, breadth 15 ft., length 15 ft., and depth 7 in.) may be approximately ascertained by means of Formula II., p. 193, namely 59 tons. Deduct from this the weight of the slab (say) 9 tons, and the remainder of 50 tons is the amount of the load in excess of the dead weight. This is so nearly equal to the load which fractured the slab, that we may conclude that the supporting of all the sides did not materially increase the strength,* or that the slab was either badly made or strained before the load was applied.

The "Columbian" System.—In this system the tension members are ribbed bars, having a vertical web and one or two pairs of lateral ribs. Fig. 61 shows two types of floors. In No. 1 the main joists of steel are encased with concrete, the concrete soffit being cast in slabs and secured by steel plates embedded in them and turned over to clip the lower flanges of the joists. In No. 2 a flat ceiling is formed by means of 1-in. ribbed bars slightly bent at the ends and supported on the lower flanges of the steel joists, which are not more than 7 ft. apart; a wooden centring is placed below the bars, and a concrete ceiling $2\frac{1}{2}$ in. thick is formed around the bars and under the joists. Openings are left in the concrete ceiling, so that the interior centring required for the floor above can be removed; the openings are afterwards closed with concrete slabs. One of the peculiar features of this system is the method of suspending the ends of the ribbed bars in stirrups placed over the steel joists; the slots in the stirrups are varied to

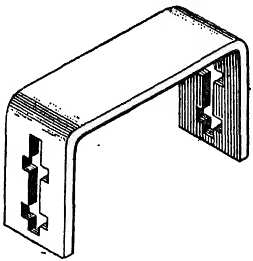


FIG. 62.—Stirrup for Supporting Ends of the Columbian Ribbed Bars.

* The fact that expanded metal offers less resistance in a direction across the meshes than longitudinally probably accounts in a great measure for the strength of the slab being so little in excess of that of a beam of the same dimensions.

suit the different sections of bars, one form being shown in Fig. 62. The ribbed bars are made in the following sizes: 1, 2, $2\frac{1}{2}$, $3\frac{1}{2}$, 4 and 5 in. deep, and are usually placed 24 in. from centre to centre; the depth of the concrete is $1\frac{1}{2}$ in. more than that of the bars, except for 1-in. bars, where the concrete is 3 in. deep. It is said

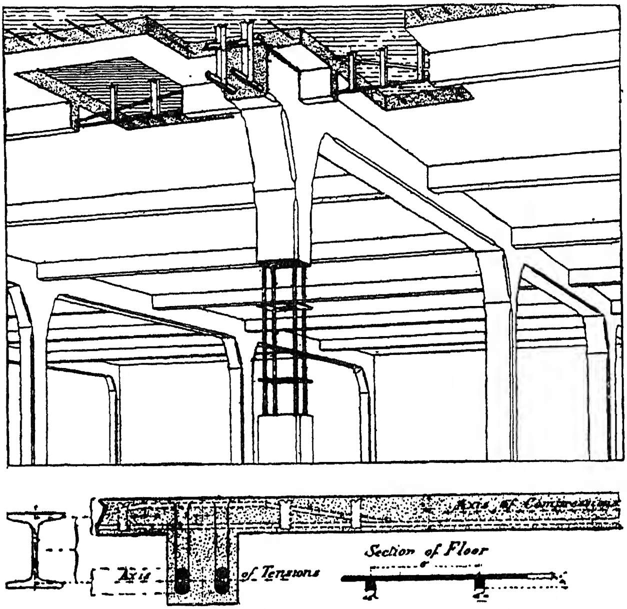


FIG. 63.—The Hennebique System of Reinforced Concrete.

that 1-in. bars will carry safely a distributed load of 125 lb. per sq. ft. over a span of 7 ft., 2-in. bars over a span of 8 ft. 3 in., and $2\frac{1}{2}$-in. bars over a span of 9 ft., and that $3\frac{1}{2}$-in. bars will carry safely a distributed load of 200 lb. per sq. ft. over a span of 14 ft., 4-in. bars over a span of 15 ft., and 5-in. bars over a span of 16 ft.

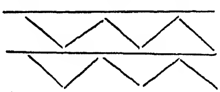
For sloping roofs the ribbed bars are laid from eaves to ridge, like the common rafters of a timber roof, the ends of

the bars being bent to the horizontal and supported in stirrups laid over longitudinal steel joists. Mansard roofs have also been constructed in a somewhat similar way.

The Hennebique System.—In this, as in the Monier system, round steel tension-rods are used. Fig. 63 gives a general view of some of the details of this system applied to the construction of columns, beams and floors, together with a section through part of the panelled floor. The rods are kept in position by means of stirrups, and over the main girders there is an upper set of transverse rods in the beams of the panelled floor, similar rods being also placed in the main girders over the points of support.

The Eggert System of flooring has square bars lying in the lower or tension part of the concrete throughout the greater part of the span, but bent upwards near the supports and turned over in hook-shape at the ends in the upper or compression part of the concrete. In some cases rods of different lengths are used in the same floor, the longest rods being bent over on the supports, the shorter rods being bent over at some distance from the supports; the quantity of metal is thus reduced. For small spans, special bricks are used in this system instead of concrete, while for larger floors, the bricks may be used to form the soffit, the concrete being deposited above them.

Mueller, Marx & Co. adopt a rather complicated reinforcement, consisting of parallel flat bars (on edge) extending from support to support, and tied together by diagonal bars, thus:



The principal bars are hooked over the upper flanges of rolled steel joists, or over rods secured to holdfasts built into the walls. The reinforcement is allowed to sag so that at the centre of the span it is near the soffit of the concrete slab, while at the ends it is in the upper half of the concrete.

3. Columns and Walls.

In columns the stresses are not entirely compressive;

there is also a tendency to rupture by swelling or bulging, and, if the load is eccentric, by bending or buckling. The reinforcement, therefore, must not be formed with vertical rods only, but these must be kept in position by horizontal ties. Some experiments by Coignet with different kinds of reinforcement show the importance of the horizontal ties very clearly. He made a number of circular concrete columns, 8 in. in diameter and 28 in. high, reinforced in various ways. The vertical rods were $\frac{3}{16}$ in. in diameter arranged in a circle, 6 in. in diameter; in series A, ring ties were placed inside the vertical rods; in series B, the ring ties enclosed the rods and were attached to them; in series C, continuous spirals were used instead of the rings. The rings and spirals were of two kinds, the first of round rods $\frac{1}{4}$ in. in diameter, and the second of flat bars $\frac{3}{8}$ in. $\times$ $\frac{1}{8}$ in. The columns with round-rod ties were, on the average, rather more than 10 per cent. stronger than those with flat bar ties. Those in series B and C were almost exactly equal in strength, and were nearly 10 per cent. stronger than those in series A. The total amount of metal was approximately 2 per cent. of the amount of concrete in all the tests, but was disposed in various ways; in the first series there were ten vertical rods (equal to 1·58 per cent. of the concrete) and seven ties (·41 per cent.—total, 2 per cent.); in the second series, there were eight vertical rods (1·27 per cent.) and twelve ties (·71 per cent.—total, 1·98 per cent.); in the third series there were six vertical ties (·95 per cent.) and sixteen ties (·94 per cent.—total, 1·89 per cent.). The third arrangement proved the strongest, although the amount of metal was rather less than in the other cases; the relative strengths were as follows:—*First* series, 100; *second*, 131; *third*, 136. These tests show clearly the importance of the ties, and seem to indicate that the amount of metal in the ties ought to be approximately equal to that in the vertical rods. In practice, the spiral ties would prove too costly, on account of the additional labour involved. The ring ties, placed outside the vertical rods and wired to them,

gave equally good results. Flat-bar ties may also be used, as in the Hennebique system (Fig. 63), where the round vertical rods are held in position by groups of four flat-bar ties holed to receive the rods.

Concrete walls may be reinforced in somewhat similar ways. As a rule piers are built to form the principal supports under the floor-beams and roof-trusses, and are connected by thinner walls. In America, many large buildings have been constructed of reinforced concrete, an interesting example being the Alabama Hotel at Buffalo, New York (Mr. Carlton Strong, architect). In this the walls are hollow as shown in Fig. 64, the total thickness being 24 in. The outer portion is 8 in. thick for the first story, and diminishes by 1 in. for each of the upper stories; as the building has six stories, the outer portion in the uppermost story is only 3 in. thick. The inner portion is 2 in. thick throughout, and is tied to the outer by concrete withs, which are 3 in. thick where the vertical rods occur and $1\frac{1}{2}$ in. thick elsewhere. The diagram shows an angle of the wall of the third story. The rods are of Ransome's twisted steel, the

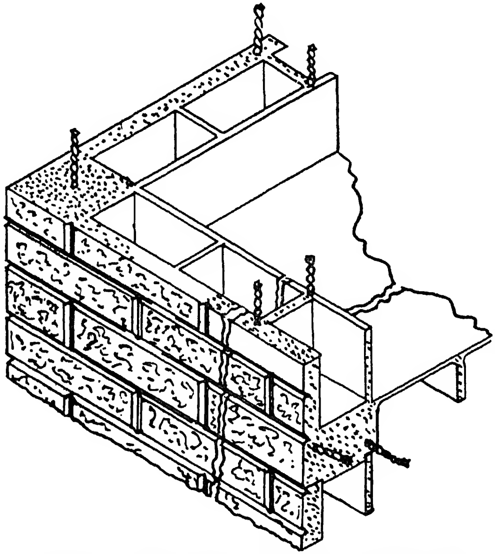


FIG. 64.—The Ransome System of Reinforced Concrete Walls.

outer verticals (which are 15 ft. apart) being 1 in. square and the inner verticals $\frac{3}{4}$ in. square; each pair of verticals is tied together by $\frac{1}{4}$-in. twisted rods, placed 12 in. apart vertically, and embedded in the concrete withs. Two $\frac{3}{4}$-in. horizontal rods are embedded in the walls at the level of each floor, the walls being built solid at these levels, except where flues for smoke and ventilation are required. The

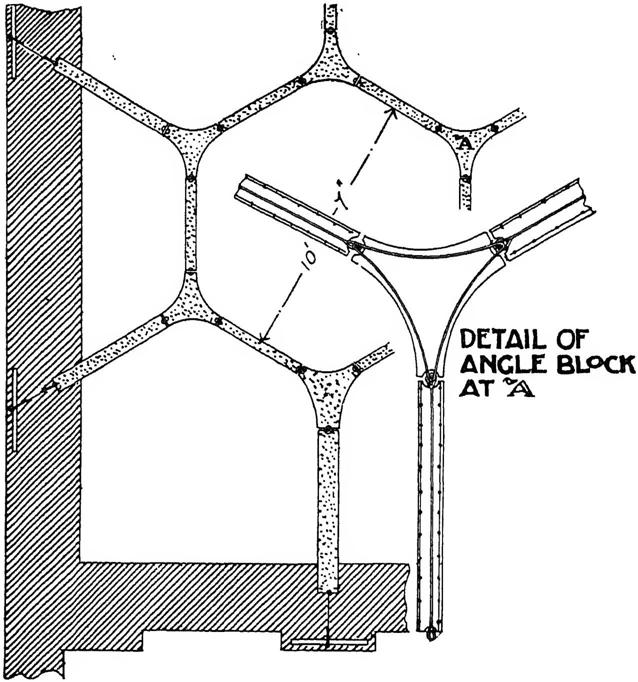


FIG. 65.—Grain-Siloes of Reinforced Concrete at Galatz, Roumania.

floors are of the panelled type already described, and the internal partitions are also of reinforced concrete. Externally, the concrete is moulded to resemble ashlar, the **V**-shaped joints being formed as described in Chapter XXIV.

The walls of grain-siloes, cement-bins, &c., have also been constructed of ferro-concrete. In the Government granary at Galatz, in Roumania, the siloes are hexagonal in shape; the largest (143 in number) are 10 ft. 7 in. in diameter and 56 feet high, each having a capacity of nearly 4,000 bushels of wheat, weighing about 100 English tons. Fig. 65 gives the plan at one angle of the building, and a detail of the angle-blocks and flat plates. The angle-blocks are about 24 in. long on each of the curved sides and $\frac{1}{2}$ metre (nearly 20 inches) high. The reinforcement consists of four tiers of round rods (nearly $\frac{7}{32}$ in. in diameter) spaced at vertical distances of 4 in., each tier being arranged in the form of a triangle with concave sides and projecting beyond the concrete at the angles in the form of loops. The flat plates connecting the angle-blocks are $39\frac{3}{8}$ in. high, and about $4\frac{3}{4}$ in. thick for the lowest 23 ft., $3\frac{15}{16}$ in. for the next $16\frac{1}{2}$ ft., and $3\frac{1}{8}$ in. for the uppermost stage. As each silo in turn may be full while those adjacent to it are empty, and *vice versâ*, the flat slabs will be alternately stressed from opposite sides. The reinforcement is therefore equal on both sides of the neutral axis, and is placed at about one-sixth of the thickness from each surface. For the first stage the horizontal tension-rods are nearly $\frac{1}{2}$ in. in diameter, and for the upper stages $\frac{1}{4}$-in., and across these are laid vertical rods ($\frac{1}{4}$ in. and $\frac{3}{16}$ in.) to form a network with meshes of about 4 in., the horizontal and vertical rods being wired together at the points of intersection. In the middle of the thickness of each slab four round rods are inserted with projecting eyes at the ends to fit over the loops at the angles of the corner blocks. Round rods 1 in. in diameter are passed through the loops and eyes vertically to connect the angle-blocks and slabs. All the abutting edges of the blocks and slabs are grooved, and the joints made with mortar or concrete. The concrete was composed of *one* part of Portland cement, $1\frac{1}{2}$ parts of sand, and $1\frac{1}{2}$ parts of fine gravel ($\frac{1}{8}$ in. to $\frac{3}{8}$ in.), the cement and sand being mixed together before the gravel

was added. A coat of cement mortar about $\frac{1}{8}$ in. thick was applied to the surfaces of the concrete after erection and well trowelled.

Reinforced concrete has also been used in the construction of factory chimneys, retaining walls, dry docks, reservoirs, filter-beds, &c., but it is impossible in the space of a single chapter to give in detail examples of every kind of structure. Some information on the subject of reinforced concrete in foundations will be found in Chapter XVIII.

4. Arched Floors, Bridges, Sewers, &c.

Arched floors to sustain heavy loads are often constructed of armoured concrete. These are sometimes of uniform thickness, or rather thicker at the springing than at the centre, but in many cases the spandrels are entirely filled with concrete to form the floor-surface. The reinforcement is often double, consisting of an upper series of rods near the extrados, and a lower near the intrados, the two series being tied together at intervals. If full advantage of the arched construction is to be taken, the abutments must be rendered perfectly rigid by means of tie-rods or in some other manner.

In the Expanded Metal Co.'s "Channel Arch Floor," arched steel channels, rising about 1 in. per foot of span, are supported on the lower flanges of the main steel joists. The channels are 6 in. wide, weighing about 12 lb. per foot, and are placed from 4 ft. to 8 ft. apart, according to the span and load. The span may range up to 25 ft. Concrete spandrels are formed over the channels up to the level of the soffit of the slab floor, which is formed with expanded metal and concrete on temporary centring as already described.

Reinforced concrete has been largely used on the Continent for bridges, and to a smaller extent in this country. Valuable information on the subject was given by Mr. E. P. Wells, C.E., in two lectures delivered at the School of Military Engineering, Chatham, in March, 1903, and published in Vol. XXIX. of the *Professional Papers* of the

Corps of Royal Engineers. The largest span described by Mr. Wells is that of the Bormida Bridge, near Millesimo, Italy, which has a clear span of 167 ft. 3 in. with a rise of 16 ft. $5\frac{1}{2}$ in. The bridge is constructed on the Hennebique system with four arched ribs 20 in. wide, and varying in depth from 3 ft. 7 in. at the springing to 1 ft. $7\frac{1}{2}$ in. at the centre. Reinforced concrete pillars rise from the extrados of the ribs to support the table or deck, on which the material forming the road-surface is laid. The whole of the bridge, exclusive of the abutments, was erected in 67 days, and was subsequently tested with a load of 226 lb. per sq. ft. (or 268 tons for the entire span) when the deflection was only $\frac{7}{16}$ of an inch; when the load was removed, it was found that there was no permanent set. Numerous illustrations and descriptions of concrete bridges, with and without metal reinforcement, are given in Mr. Wells's lectures, and the reader interested in this branch of engineering will find them worthy of careful perusal.

For large sewers and water conduits, reinforced concrete has been successfully used. In the Monier system, a network is formed by means of longitudinal and circumferential rods, wired together, the whole being embedded in concrete. The Columbian system differs from this principally in the shape of the longitudinal bars, which are similar in section to those used in the Columbian floors. Expanded metal is also used for the reinforcement, as in Fig. 65, which is a section of one of the conduits in connection with the Torresdale Waterworks, constructed for the city of Philadelphia. The internal dimensions are—width, 9 ft. 8 in., and height 10 ft.; the upper portion is a semi-ellipse, and the invert a segment of a circle joined to the ellipse by two circular segments of shorter radius. The thickness of the concrete at the springing of the semi-ellipse is 16 in., and at the crown 10 in. The expanded metal has a 6-in. mesh, with strands $\frac{1}{2}$ in. in width, and is placed as shown by the dotted lines. The centring was in seven segments, covered outside with sheet-iron, which

was cleaned and oiled before the concrete was deposited. Fine concrete 1 in. thick, composed of equal parts of Portland cement, sand and "granolithic grit," was laid on the centring to form the inner surface of the conduit, the remaining concrete consisting of *one* part of Portland cement, *three* parts of sand, and *five* parts of broken

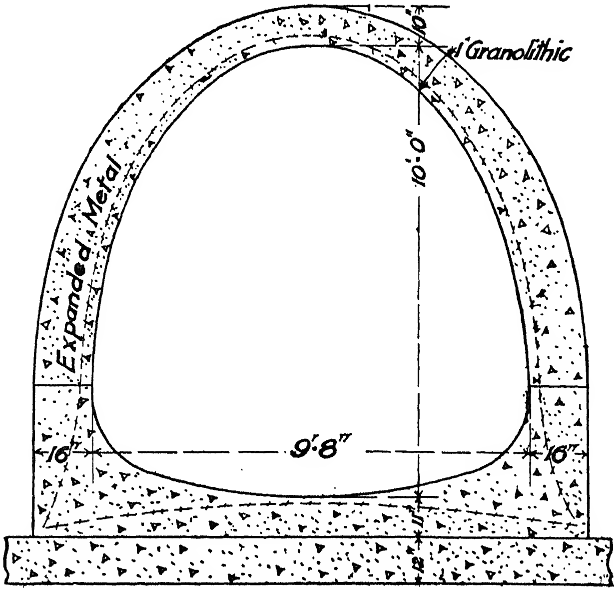


FIG. 66.—Reinforced Concrete Conduit, Torresdale, Philadelphia.

stone ($\frac{3}{4}$-in. gauge). The conduit was designed to withstand the pressure due to a head of water of "about 20 ft."

Staircases are often constructed of reinforced concrete, either in the form of steps separately moulded and built into the walls like stone steps, or deposited *in sitû* around the meshwork of rods. Among other uses of the material may be mentioned piles, telegraph poles, coal-bunkers, tanks, and baths.

5. Notes on Concrete for Reinforced Structures.

Cement.—The Portland cement should be of the best quality, free from all deleterious ingredients, and very finely ground. Mr. E. P. Wells's experiments show that all residues left on a sieve with 160 meshes to the lineal inch are inoperative, but that the flour obtained by grinding these residues is stronger than the flour of the original cement, the more resistant particles being the best-burnt portion of the clinker. The tensile strength of briquettes of cement and sand (1 to 3) should not be less than 180 lb. per sq. in. at seven days, and 300 lbs. at 28 days.

Sand.—This should be sharp, not too uniform in size, and absolutely clean. Any coating of mud or clay is injurious. The fine stuff obtained by crushing Portland stone gives excellent results, as far as strength is concerned, but, for fire-resisting structures, this and other limestones are unsuitable. Ordinary siliceous sand, either natural or obtained by crushing good sandstone, is better in this respect.

Aggregate.—Thames ballast is a satisfactory material, if it is thoroughly washed, and if all the sand and all the pieces retained by a $\frac{3}{4}$-in. mesh are excluded. For concrete upwards of 3 in. in thickness, the larger pieces may be broken to pass a screen with 1 in. meshes, and added to the finer material. Granite and the allied rocks are also suitable. Crushed Portland stone is one of the best aggregates for many purposes, but as all limestones are quickly disintegrated by fire, it is not recommended for fire-resisting construction.

Water.—The water should be as pure as possible, free from mud and organic impurities. For nearly all purposes fresh water is better than sea water, the latter being quite unsuitable for use in buildings.

Proportions.—As the strength of concrete depends to a very large extent on the strength of the mortar in which the coarser parts of the aggregate are embedded, an excess of sand must be avoided. What is required is a mortar which will suffice to fill the voids in the aggregate and to

bind the particles together. As a rough guide, it may be said that the volume of sand should be one-fourth that of the sand and coarser aggregate. Thus: for 4 to 1 concrete, use 1 part sand, 3 parts coarser aggregate, and 1 part cement; for 6 to 1 concrete, use $1\frac{1}{2}$ parts sand, $4\frac{1}{2}$ parts coarser aggregate, and 1 part cement. If the concrete is thoroughly rammed, these proportions will yield a solid mass. A porous aggregate should be soaked in water before being made into concrete, as otherwise it would absorb the water required for the setting and hardening of the cement. An excessive quantity of water is injurious, but is often used, as it facilitates the deposition of the concrete. Better results are obtained by using a smaller quantity of water, and by thoroughly ramming the concrete to render it solid. For floors, roofs, partitions, and other thin structures, 3 or 4 parts of aggregate to 1 part of cement are the most suitable, but a greater proportion of aggregate may be used for foundations, thick walls, bridges, &c.

Mixing, &c.—Machine-mixing is the best, but where a good machine is not available, the materials may be mixed by hand. Many modern specifications require the ingredients to be turned three times dry and three times after the water has been added. Care should be observed that the workmen use their shovels in such a manner as to mix the materials thoroughly. The concrete should be deposited immediately after it is made, and should be well rammed, so that the concrete is packed tightly around the reinforcement and so that all voids are eliminated. It must also be protected from extremes of temperature during the process of setting and hardening. In large structures the day's work should be regulated, so that the joint between the masses of concrete laid on different days will not be injurious; thus, in a flat floor the joint must fall over a girder or in a straight line at right angles to the supports; in a large arch the joint must be radial, like the joint between two stone voussoirs. Finally, the temporary centring must be of ample strength, so that it does not deflect under the weight of the wet concrete and of the men employed in the work.

INDEX.

THE END.

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